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Cybernetic Modelling

CYBERNETIC MODELLING

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PREFACE

The principal purpose of this book is to show the part played by cybernetic modelling in the solution of problems common to the animate and inanimate world. The system, its behaviour and structure are used here as fundamental concepts forming the basis of a wide approach that utilizes the model as a methodological instrument. In our book we had, of course, to confine ourselves to certain problems of cybernetic modelling only. The selected subject matter will be seen to fall into three parts:

Part One (Chapters 1 to 8) is devoted to a general explanation of the principle of modelling with special regard to its cybernetic aspects. This part also comprises a short review of abstract and physical aids to modelling. For didactic reasons, considerable attention has been paid to a detailed exposition of logic nets, by means of which the principle of modelling is illustrated with concrete examples.

Part Two (Chapters 9 to 11), the smallest in extent, deals with an entirely different aspect of the matter. Its aim is to present a rough outline of those problems in biology that are of interest from the cybernetic point of view, and to draw attention to some biological systems whose modelling may in the future assume great importance to technology as well as to biology itself. Our exposition in this part — although it may be critically received by biologists — is intended as a very rough and approximate introduction for engineers. We know from our own experience how difficult it is for these workers to find their bearings in the sphere of biology. In order not to exceed the allotted space, we had to confine ourselves in many places to referring the reader to the relevant literary sources.

The most extensive part is Part Three, which is devoted to some concrete studies in the field of cybernetic modelling. These studies are mostly concerned with the psychological manifestations of higher living organisms and with their modelling by inanimate systems. Chapter 15 plays a special role — it deals with the problem of the "understanding" of texts by machines. From the viewpoint of modelling, the exposition in this chapter digresses to a certain extent into linguistics.

It should be emphasized that this book is not popular in the common sense of the word. However, it is intended to be accessible to experts from diverse fields who are interested in the problems presented here. A cursory first reading will give a general idea of the problems of cybernetics. A more profound understanding, however, requires careful study and independent considerations on the part of the reader.

In some parts of the book we draw upon the works and ideas of our teacher, Dr. ANTONÍN SVOBODA. We also make use of the discussions held by a small group of cyberneticists using the pseudonym K. VASSPEG.

The book is supplemented by a detailed list of the most important literature relating to the given theme. The list is divided into four parts, denoted A to D. The publications have been numbered within their own parts. References are given under the pertinent letter and number, e. g. [C15].

It is our pleasant duty to thank all our fellow-workers for their valuable suggestions. Most of all, we want to express our deep gratitude to Prof. Dr. OTAKAR ZICH, whose generous co-operation we greatly appreciate. Prof. Dr. ZICH was kind enough to give the manuscript a careful perusal. Following his suggestion, some very fruitful conversations were held which provided an excellent opportunity for discussing the entire text of the book.

Special mention is due to Mr. P. DOLAN, M.Sc., who translated the manuscript into English. He deserves our thanks not only for the care he devoted to the translation, but also for his valuable suggestions and comments concerning the subject of the book.

Prague, 1965 J. KLÍR and M. VALACH

Part One

CYBERNETIC MODELLING
AS A METHODOLOGICAL APPROACH

CHAPTER 1

INTRODUCTION

The basis of our world is *matter*, which is in continuous motion in space and time in the widest sense of the word.

The existence of matter shows itself in the most diverse forms, by the aid of which it affects our sense organs either directly or through measuring instruments. The difference between these forms consists primarily in the degree of the amount of organization of matter. Transition from lower, less organized forms of the manifestation of matter to higher, more highly organized forms is one of the most important properties of the motion of matter from the standpoint of our existence.

It is customary to divide matter according to its state of organization roughly into inanimate and animate matter. *Inanimate matter* represents lower forms of the state of organization whereas *animate matter* is closely linked with higher forms. The difference between animate and inanimate matter manifests itself in that animate matter possesses, owing to its high degree of organization, some qualitatively new properties which do not occur in inanimate matter.

Out of the totality of matter we can study only finite parts in finite time. These parts are thus the *objects* of our investigation. It is of advantage to study, in these objects, *systems* accurately defined in space and time and clearly distinguished from their *environment*. The definition of a system in a distinct object represents the standpoint from which we want to study this object. In systems we are usually interested, on the one hand, in their internal functional relationships, on the other hand in their external relations to the environment. In the first case we shall speak of the *structure* of the system (Sec. 2.10), in the second case of its *behaviour* (Sec. 2.7). In a similar sense we sometimes also speak of the structure and behaviour of an object; in this context, however, the meaning of the terms quoted above is not as accurate as in systems.

Every material object in nature is unique, i. e. it exists only in a single form. However, if we define a certain system in this object in such a manner that it possesses only properties which exist from a certain standpoint, several objects may exist in which we can find systems satisfying the corresponding definition. In such a case we speak of a class of systems. On the basis of the definition of the system it is then always possible to determine whether two systems belong to the same class (Sec. 2.5).

The task of scientific research is to find laws describing whole classes of systems and not only unique systems. Therefore, when speaking of a system in the scientific sense, it is always a class of systems we have in mind.

Physical systems may be animate, inanimate, or combined, according to whether they contain animate, inanimate, or both kinds of matter.

One of the fundamental properties of animate matter is that it organizes itself into well-defined objects which exhibit a characteristic behaviour. Such objects are independently *living units — living individuals*. As already mentioned, their behaviour shows some properties qualitatively differing from those of inanimate systems. The study of these properties, which depend on the characteristic chemical and physical structure of living matter, forms the subject of the biological sciences.

One of the most interesting properties of animate matter is that it is capable of organizing its own structure. At a certain stage of organization it extends this capability to its environment in the sense that it can, on the one hand, affect the organization of other animate objects and, on the other hand, organize even inanimate objects. A living individual can use this faculty in arranging his local environment, to a certain extent, to suit his comfort and convenience.

The simplest type of a living individual is the cell; the most complicated and most highly organized type known to us is man. The aggregate of all individuals of this species on our planet forms the most complex and most highly organized animate system known to us — human society. However, the faculty of organizing his environment is not restricted exclusively to man. Other organisms also possess this faculty, though at different levels.

One of the supreme methods by which man affects his environment involves organizing inanimate systems so that they acquire, in some

respects, a behaviour analogous to that of animate systems. These inanimate systems are said to simulate the behaviour of living systems. Such modelling affects not only our ideas, but even the relation between animate and inanimate matter.

The problem of the relation between animate and inanimate matter has excited the interest of mankind since ancient times. Investigations in this field have proceeded, in principle, along two lines. The first of these aims at the artificial creation of living matter, the other attempts to simulate various functions of living organisms and especially different manifestations of man by means of inanimate systems.

Even though much effort has been expended throughout the history of mankind in attempts to create living matter artificially, this aim has not yet been achieved. Investigations have shown that living matter is constituted most likely of complexes of some high-molecular carbon compounds (chiefly proteins, nucleic acids and polysaccharides) which contain between thousands and hundreds of thousands of atoms of the constituent elements (in addition to carbon these are mainly hydrogen, oxygen and nitrogen). The chemical structure of most of these compounds is not fully known. It has been proved, however, that they are formed in accordance with certain rules of simpler low-molecular compounds which have already been artificially produced but do not by themselves constitute life. We have not yet succeeded in producing artificially the high-molecular organic compounds of which living organisms consist. Still less has it been possible to "manufacture" living individuals, such as cells, which are highly complicated systems containing whole complexes of high-molecular substances arranged in a certain order.

Interesting results have been obtained only recently in the modelling of various functions of living organisms with the aid of inanimate systems – *engineering models.* We are here concerned with inanimate systems, the behaviour and structure of which simulates the behaviour and structure of animate systems. The simplest models of this kind were already known at primitive stages of civilization. The first of these were various simple mechanisms used for hunting animals; in a changed form they were later used for different other purposes also. A common feature of all such mechanisms is that they simulate only very simple elements of behaviour in living individuals – *unconditioned reflexes.*

Later on, especially in connection with the development of the watch-making art in the 17th and 18th centuries, models of greater complexity were produced which simulated certain sequences of unconditioned reflexes. At first these were only toys made in the shape of various animals. The internal mechanisms of these toys were driven by clock-work and performed actions (e.g. motions, sounds, etc.) which resembled the behaviour of the corresponding animal. There is certainly no need to emphasize that modelling of this kind is on a very low level not only from the standpoint of structure, but also from that of behaviour. As we know, these models keep performing the same action and cannot adapt their behaviour to changes in environmental conditions. But even this simple type of modelling proved later, in a more complicated form, of great importance to the development of mechanical engineering in the 19th century. At that time, various devices came into use which were capable of performing by themselves certain sequences of uniquely determined operations. Among them were, for instance, automatic machine tools, looms, printing machines, and many others.

As a matter of interest, a device involving the concept of automation was described as long ago as 1588. This was the well-known device used for controlling the speed of rotation of mill-stones in watermills in accordance with the hardness of the grain and the flow of water [A9]. Its principle of operation consisted in that the rotation of the mill-stones imparted, with the aid of a profiled shaft, a rocking motion to the slightly inclined trough which brought the grain to the stones. The faster the stones rotated, the more intense was the shaking of the trough, and the greater the amount of grain supplied to the mill-stones. A surplus of grain caused the motion of the stones to be slowed down and thus resulted in a reduction in the supply of grain, and vice versa.

Another well-known example of automation is Watt's classical centrifugal governor still used for regulating the speed of steam engines. Among other known simple devices in this field are, for instance, the thermostats used to maintain a constant temperature in closed spaces (refrigerators, aquaria, etc.), Wagner's interrupter where a spring with a small hammer is kept vibrating at a given frequency, or the float and needle in the carburettor of an internal-combustion engine, which keep the fuel level in the float chamber at a constant height.

Important progress was made in the development of automation when it proved possible to utilize some inanimate systems for storing signals arriving from the environment. Systems of this kind are generally named "*memories*", a term which recalls the analogy of the function of these devices with the function of the memory in higher organisms.

Devices with memories acquired a qualitatively new property in that they are capable of modelling higher elements in the behaviour of living individuals – *conditioned reflexes*. Models of simple unconditioned and conditioned reflexes can be combined to form models of rather complicated behaviour in living systems, e.g., behaviour aimed at achieving a certain goal, learning, behaviour based on experience, or even the endeavour to retain the normal function of the model as long as possible, and many other higher types of behaviour.

We have already mentioned that animate matter can, at a certain stage of development, organize its enviroment and thus increase the amount of organization even in inanimate systems. With the progressive development of animate matter this capacity grew steadily until it suddenly changed, at a certain stage, into a new quality. This happened in 1953, when it was proved in a computer [B 14] that even inanimate systems may acquire the capability of organizing themselves in a required manner and thus show the capacity of evolving themselves. The study of inanimate "*self-organizing*" systems is nowadays a subject of great scientific interest.

The production of increasingly organized inanimate systems, especially of self-organizing inanimate systems, contributes to an extraordinary degree to the elucidation of the problem of the relation between animate and inanimate matter. An increasing number of similar traits is being discovered in the behaviour of animate and inanimate systems respectively. These common features, many of which were originally the exclusive property of animate matter, cease being the exclusive domain of biology. However, neither are they characteristic of physics, chemistry, or other existing branches of science since, from the standpoint of these fields, processes in animate and inanimate matter appear differently, even though their behaviour may be similar. A new branch of science, which would treat animate and inanimate physical systems from the standpoint of these similarities, appeared to be necessary. For the new branch of

science which arose from the aforesaid requirements the name of *cybernetics* has been adopted.

The meaning of cybernetics, however, is not always clearly understood. Usually, cybernetics is erroneously supposed to deal with the study of some new objects which formerly escaped our attention. Actually we are concerned here with the same objects which have already been studied by physics, chemistry, or the biological sciences in a wider sense; we are interested, however, in the new point of view from which systems are defined in these objects. The introduction of this new point of view proved so useful for the further and more profound study of some objects, that at a certain stage in the development of science it appeared expedient to establish, as already mentioned, a new branch of science for it. Thus, cybernetics did not come into being in order to study quite definite objects (such as has been done, for instance, by biology in its relation to physics), but as a *new methodical approach* instigated by the endeavour to improve the efficiency of scientific work.

Before proceeding with a more precise statement of the aforementioned point of view and a definition of cybernetics, we must first elucidate the concept of a *system*.

CHAPTER 2

SYSTEMS

We already encountered the term "*system*" several times in the introductory chapter. We are here concerned with a fundamental concept in the sense of the aim of this book. We shall therefore clarify and supplement it by a more detailed explanation. However, we shall confine ourselves in this chapter to the exposition of general notions to be used in the subsequent text. The more profound analysis of some properties, chiefly concerning cybernetic systems, will be left to Chapter 4.

2.1 FUNDAMENTAL PROPERTIES

In general, a system is defined as a *set of interrelated elements* (see Sec. 2.8).

Every system has its *environment*. With physical systems the environment is theoretically everything that is not included in the given system. However, since we confine ourselves mostly to a finite number of defined relations between the system and its environment, it is usually of advantage to restrict oneself to the *substantial environment*, i. e. to a limited set of elements which interest us in the environment. The same applies to abstract systems. We must realize, however, that we are never interested in the relations between the elements of the environment. For, if we were interested in them, we would denote the pertinent set of elements and their relations not as the environment, but as a system.

The physical system and its environment act on each other – they *interact*. The manner in which a system influences its environment depends, in general, on the properties of the system itself as well as on the manner in which the environment acts on the system. Conversely, the same applies to the environment.

In abstract systems we are not concerned with actual interactions, but with mutual relations between their properties. However, in order to form a unified view of systems, we may even in abstract systems interpret the corresponding relations as interactions.

According to the kind of interaction between the system and its environment, the following three types of system are sometimes distinguished:

1. *Absolutely closed systems*, where no interaction with the environment is considered.

2. *Relatively closed systems*, where the paths over which the environment acts on the system (inputs of the system) as well as the paths over which the system acts on the environment (outputs of the system) are accurately defined.

3. *Open systems*, where we consider all possible effects of the environment on the system and vice versa.

We do not consider the classification of systems as given above to be entirely suitable. As already follows from our first reflections in the introduction we consider, in this book, a system always as a relatively closed one. Instead of the notion "*open system*" we use the term "*object*". When speaking of a closed system, we must realize from which point of view the system is meant to be closed. This may be, for instance, from the standpoint of the exchange of matter, energy, information, etc. We may then speak of systems closed only from the standpoint of the exchange of information, from that of the exchange of matter, etc.

In this book we shall be interested mostly in systems closed from the viewpoint of the exchange of matter and energy, but relatively closed from the standpoint of the exchange of information. Even though we shall include absolutely closed systems in our considerations, they will be conceived as special and comparatively little interesting instances of relatively closed systems.

In order to describe different types of system by a language, we shall henceforth denote all effects of the environment on the system as *stimuli*, and all effects of the system on its environment as *responses*.

In every system we shall distinguish two basic properties which characterize it, namely

1. its *behaviour*,

2. its *structure*.

We shall speak of the behaviour of a system (see Sec. 2.7) only if both its input together with the corresponding stimuli and its output with the corresponding responses are defined. Under behaviour we understand the dependence of responses on stimuli.

We also speak of the behaviour of the elements of a system, because in them we are again concerned with systems which, however, are considered globally, i.e. from the standpoint of the given system we are interested only in the behaviour of its elements but not in their structure.

By the structure of a system (Sec. 2.7) we understand, on the one hand, the manner of arrangement (organization) of the mutual couplings between the elements of the system (see Secs. 2.9 and 2.10), on the other hand the behaviour of these elements.

2.2 EXAMPLES

To elucidate the concepts introduced in the foregoing section, let us now present some examples of quite heterogeneous objects in which systems can be defined from different points of view:

1) *Scissors.* These consist of two elements (blades), interconnected spatially as well as functionally. Each element has one input (handle) and one output (the blade). Stimuli cause changes in the position of the handles, the response manifests itself by a change in the position of the cutting edges. The effects on the environment can be destructive!

2) *Billiards.* The elements of the system are the billiard-balls. Functional relations between the elements are assessed from the viewpoint of the position, speed and rotation of the ivory balls. The environment acts on the system in the form of gravitation, friction, and of the external actions of the players. The response of the system upon its environment manifests itself, for instance, by the pressure of the balls in motion on the billiard-table, by their collisions with the cushion, etc.

3) *Domestic electrical installation.* The elements are switches, lamps and other appliances. Coupling between the elements is provided by the interconnecting wires. Stimuli arrive from the switches, responses manifest themselves in the appliances.

4) *Slot machine.* Compared with the foregoing examples, the structure of this system is more complicated. Its behaviour manifests itself in that, on inserting the prescribed coins and depressing the appropriate push-buttons or levers, the desired kind of ware drops out.

5) The system which realizes *the mathematical function* $z = 2x + y^2$. This system has two inputs, x and y, and one output, z. Its behaviour manifests itself in that we obtain for different values of the independent variables (stimuli) the corresponding value of the dependent variable z (the response). The system comprises three elements: an element for multiplying by two, an element for raising to the second power, and an adding element. The couplings (see Chapter 5) are made clear by the formula given above.

6) *Animals.* These are complex objects which are, however, clearly distinguishable from their environment. When studying them we are forced to confine ourselves always to a single point of view, by which we define the corresponding relatively closed system. The behaviour of this system depends in general on the whole sequence of stimuli which have acted upon it from the moment of its birth.

7) *The brain.* This is a clearly restricted system which occurs in higher animals. On the average, it consists of about 10^{10} elements (neurons). Stimuli enter the brain from receptors via centripetal (afferent) nerve fibres and reactions leave it over centrifugal (efferent) fibres and terminate in effectors.

2.3 Resolution Level

Let us consider some system, e.g. the aforementioned billiards. This is a system defined at the resolution level of our sense organs (sight, touch). Should we raise the resolving power, for instance, as far as the molecular level, the object of our consideration would be a differ-

ent system. Each ball by itself would be a system with an enormous number of elements and immensely complicated couplings between its elements and with the elements of the other balls.

However, in the case mentioned above we are not interested in increasing the resolution, since our own resolving power not only satisfies us, but is even desirable. In many other instances, on the contrary, we endeavour to study systems at increasingly high resolution levels. An example of such a system is the brain, where we strive to determine the individual functional centres more accurately and more subtly in order to find the laws governing the structure of the neuron network and to study even single cells as systems. In this respect the resolving power of our sense organs is unsatisfactory and we must invoke the aid of various artificial expedients (e.g. microscopes, recording methods of measurement utilizing microelectrodes inserted in the brain, etc.). A single molecule (see Sec. 9.3) or even a single atom may also constitute a system.

Various systems are thus studied at different resolution levels. In some systems we content ourselves with a low resolution level, a higher one being undesirable. In others we want to look at the system from the highest possible resolution level. We are, however, usually limited by the level of our technical resources.

2.4 Resolution Graphs

Different resolution levels, by means of which systems can be defined for a given object from a certain point of view, can be represented very well by an oriented graph*) which has the properties of a mathematical lattice.**) Such graphs will be termed *resolution graphs.*

Each node of a given resolution graph corresponds to a single aspect from which a single object is assessed. Each of these nodes expresses, however, the view at a different resolution level. Thus, from the view-

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*) An oriented graph is regarded throughout this book in the sense of reference [C 3], i. e. as a non-empty set of points combined with a non-empty set of oriented connecting lines between these points.

**) The theory of lattices will not be treated in this book. The serious reader is referred to [C 5].

point of different aspects, the objects of interest are different systems, $\mathbf{S}_1, \mathbf{S}_2, \ldots$ (Fig. 2.1).

The terminal (lower) node of the resolution graph (always denoted by $\mathbf{S}_1$) corresponds to the lowest possible resolution level; no connecting line originates in it. At this lowest resolution level only the behaviour of the corresponding system is known to the observer, but none of its structural properties.

When passing through the resolution graph to higher nodes (in a direction opposite to the orientation of the connecting lines) the resolution

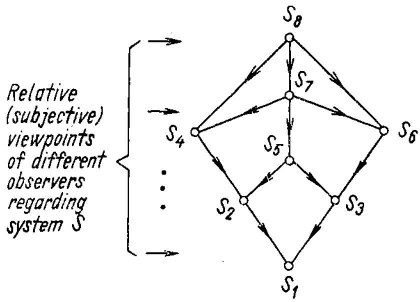

Fig. 2.1. Example of a resolution graph

level increases. This increase in resolution level may occur in various directions; this is represented in the resolution graph by several connecting lines entering a single node.

Every resolution graph has a single starting (upper) node ($\mathbf{S}_8$ in Fig. 2.1) in which no connecting line terminates. This node corresponds to the highest desired resolution level (e.g. as far down as the level of the atomic nucleus).

The resolution graph is sometimes very simple. E.g., Fig. 2.2 represents the resolution graph for the case of the aforementioned billiards. As will be seen, we are concerned here with a straight graph, since in this case the resolution level is raised in a single direction only. Usually, however, it is possible to increase the resolution level in several directions. For instance, in a radio receiver we may be interested, in addition to its block diagram, in more detailed diagrams of some of its circuits, e.g. the I.F. amplifier, the power supply, etc.

Let us note that the process of perceiving a certain object from a given point of view begins always at the lowest node of the resolution graph. At this state of cognition we do not know anything about the corresponding system, but we can observe its behaviour. In this case we regard the system as an indivisible block including input and output. As our knowledge increases, the block will be seen to fall into partial blocks interconnected in various ways according to the nature of the system.

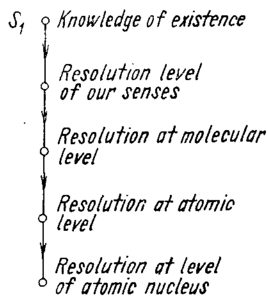

Fig. 2.2. Resolution graph for billiards regarded as a system

In this manner we proceed along the connecting lines of the resolution graph in an upward direction.

In this process we must draw a distinction between hypotheses concerning the properties of the system under investigation and verified facts. Hypotheses are always at a higher level in the resolution graph, since they are always to some degree in advance of verified knowledge.

In this book we shall repeatedly return to the concept of the resolution graph, especially in connection with modelling procedure (see Chapter 5).

2.5 Definition of a System

In this section we are going to introduce some new concepts to be used in the enunciation of the definition of a system. At the same time we are going to introduce for these concepts mathematical symbols which will be strictly adhered to in our further exposition.

Let the system **S** contain the elements $a_1, a_2, \ldots, a_n$ and let a_0 be the environment of system **S**. Let us introduce the set $\mathbf{A} = \{a_1, a_2, \ldots, a_n\}$ and the set $\mathbf{B} = \{a_0, a_1, \ldots, a_n\}$. Set **A** consists only of the elements $a_1, a_2, \ldots, a_n$ of the system **S**, whereas set **B** includes not only these elements, but also the environment regarded here as a separate element a_0.

Let every element of the set **B** be characterized by a set of input quantities and a set of output quantities. Let the symbol $\mathbf{r}_{ij}$ denote the manner in which the input quantities of element a_j depend upon the output quantities of element a_i, which follows from the relation between these quantities. The set of all $\mathbf{r}_{ij}$ $(i, j = 0,1,\ldots,n)$ will be denoted by **R**.

We have thus introduced a sufficient number of concepts to proceed with the definition of the system which will form the object of our further inquiry.

A system is defined by the statement that every set $\mathbf{S} = \{\mathbf{A}, \mathbf{R}\}$ constitutes a system.

If $\mathbf{r}_{0i} = 0$*) and simultaneously $\mathbf{r}_{i0} = 0$ for all values of $i = 1,2,\ldots, n$, we are concerned with an absolutely closed system, in all other instances with a relatively closed system. It is easy to show that a relatively closed system containing n elements may be regarded as an absolutely closed system containing $n + 1$ elements and vice versa.

From the definition of the system it also follows that a system may contain even *isolated elements*, i. e. elements for which $\mathbf{r}_{ij} = 0$ with respect to other elements. Thus, for an isolated element a_i we have $\mathbf{r}_{ij} = 0$ for all values of $j \neq 1$. Similarly there may exist *isolated groups of elements*, characterized by the fact that for each element of such a group we have $\mathbf{r}_{0i} = 0$ and simultaneously $\mathbf{r}_{i0} = 0$.

We see that isolated elements as well as isolated groups of elements do not take part in the interaction of the system with its environment. Thus, in many cases they need not be considered at all. It is therefore sometimes useful to define the system in such a way that isolated elements

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*) The symbolic notation $\mathbf{r}_{ij} = 0$ is introduced as an abbreviated statement of the fact that, in the system concerned, the element a_i exerts no influence on the element a_j, the relation being not always necessarily quantitative.

or isolated groups of elements are not included in the definition. In such a case we shall speak of a reduced system.

The reduced system is defined as follows:

If

a) $\mathbf{r}_{0i} \neq 0$ *for all values of* $i = 1,2,\ldots, n$

b) $\mathbf{r}_{i0} \neq 0$ *for all values of* $i = 1,2,\ldots, n$

then the set $\mathbf{S} = \{\mathbf{A}, \mathbf{R}\}$ *is a system.*

According to both definitions given above a system is thus a set $\mathbf{S}$ made up of set $\mathbf{A}$ and set $\mathbf{R}$. Set $\mathbf{A}$ is frequently called *the universe of the system,* and set $\mathbf{R}$ *the characteristic of the system.* These designations will be retained throughout this book.

2.6 Types of Problems

We mentioned already that a system is characterized by two fundamental properties – its structure and behaviour. These two properties are very closely related; their relation can be expressed by two statements:

1. A definite behaviour corresponds uniquely to a certain structure.

2. To a definite behaviour there corresponds a class of structures defined by this behaviour.

In principle, problems concerning systems in whatever manner can be roughly classified as follows:

a) The system does not yet exist; its structure is to be designed so that the realized design exhibits the prescribed behaviour.

b) The system already exists (in fact or only as a design) and its structure is known (or can be ascertained); its behaviour is to be determined on the basis of the known structure.

c) The system already exists (in reality) but nothing is known about it and its structure cannot be determined directly; the problem consists in ascertaining the behaviour of the system and with its aid, if possible, the structure.

In the first case we speak of the synthesis of systems, in the second case of their analysis, and in the third case of the problem of the "black box".

The synthesis of systems finds use most frequently in various branches of engineering. Since a specified behaviour does not always lead uniquely to a definite structure, different additional demands may be made on it (e.g. requirements concerning lowest costs, reliability, simplicity of operation, etc.).

Analysis leads always to a unique solution. It is used predominantly in engineering, either when verifying the design of various engineering equipment or when elucidating the function of devices of which nothing is known at first, the structure of which can, however, be ascertained by observation.

The problem of the black box can be solved only by a single procedure: assessing the behaviour of the given system by experimentation (see Sec. 2.7) and inferring its structure from the behaviour. As long as we have no data on the structure of the system under investigation, we can never be certain of having fully solved the problem of the black box in the corresponding system. This is due, on the one hand, to the fact that no amount of experimentation with the black box will guarantee a complete disclosure of its behaviour (see Sec. 8.10), and on the other hand to the fact that a definite behaviour is always associated with a whole class of possible structures. However, if we are in the possession of certain data on its structure (we know, for instance, that it is designed in the most economical manner, or we are looking for pathological changes in a system whose normal structure is known, etc)., then we can be certain, in some cases, that the problem of the black box has been fully solved, i.e. including the disclosure of its actual structure. Whether this is possible must be decided separately in every concrete case.

Even though the problem of the black box frequently occurs in various forms in engineering (e.g. when tracing faults in some piece of equipment on the basis of changes in its behaviour), its principal domains are some of the biological sciences (e.g. physiology, embryology, biochemistry, etc.) and particularly psychology, psychiatry, pedagogy.

Summing up concisely the basic types of problems concerned with systems, we get the following scheme:

1. *Synthesis:* behaviour (+ requirements concerning structure) → structure.

2. *Analysis:* structure → behaviour

3. *Problem of the black box:* black box (+ partial knowledge of its structure) → experiment → behaviour → structure.

We shall return to the basic types of problem relating to systems in Sections 2.13 to 2.15 where we shall already be able to base our investigation on the explanation of behaviour, structure, and the classification of systems.

2.7 BEHAVIOUR

Every relatively closed system has its *input* and *output*, by means of which it interacts with its environment. Let us assume that the input (or output) consists in general of *partial inputs* (or *partial outputs*), each of which is sensitive (selective) to a single property only. In the general considerations to follow we shall always denote the number of partial inputs by the symbol p ($p \geqq 1$), the number of partial outputs by the symbol q ($q \geqq 1$).

It should be realized that the properties appertaining to the partial inputs and outputs may form the base from which we start when defining a system in an object. In such a case, the elements of the system and their correlations cannot be defined before analysing the causes which create certain relations between the corresponding properties.

The instantaneous value of the signal in the partial input (or output) will be termed partial stimulus (or partial response, respectively). Partial stimuli are denoted by $x_1, x_2, \ldots, x_p$, partial responses by $y_1, y_2, \ldots, y_q$.

Partial stimuli can be regarded as components of a vector in a p-dimensional space. Let us denote this vector by $\mathbf{x} = (x_1, x_2, \ldots, x_p)$ and call it the input (stimulus) vector or, in short, the stimulus. In a similar manner, partial responses may be regarded as components of a vector in a q-dimensional space. This vector is denoted by the symbol

$\mathbf{y} = (y_1, y_2, \ldots, y_q)$ and called the output (response) vector, or briefly the response.

Diverse stimuli (states of the vector $\mathbf{x}$) will be denoted by ${}^1\mathbf{x}, {}^2\mathbf{x}, \ldots$, and similarly diverse responses (states of the vector $\mathbf{y}$) by ${}^1\mathbf{y}, {}^2\mathbf{y}, \ldots$.

The behaviour of a system can be expressed in general as the transformation $\boldsymbol{T}$ of the vector $\mathbf{x}$ into the vector $\mathbf{y}$, i. e. by the relation

$$\mathbf{y} = \boldsymbol{T}(\mathbf{x}), \tag{2.1}$$

where $\boldsymbol{T}$ is the operator of the transformation.

In a system, the transformation (2.1) can be either single-valued or many-valued. In a single-valued transformation every stimulus is associated with a single response. Partial responses are therefore, in this case, functions of partial stimuli. Thus

$$\begin{aligned} y_1 &= f_1(x_1, x_2, \ldots, x_p), \\ y_2 &= f_2(x_1, x_2, \ldots, x_p), \\ &\ldots\ldots\ldots\ldots\ldots\ldots, \\ y_q &= f_q(x_1, x_2, \ldots, x_p), \end{aligned} \tag{2.2}$$

or, in vector form,

$$\mathbf{y} = \mathbf{f}(\mathbf{x}), \tag{2.3}$$

where $f_1, f_2, \ldots, f_q$ are functions of p independent variables $x_1, x_2, \ldots, x_p$, and $\mathbf{f}$ is the vector function of the independently variable vector $\mathbf{x}$.

The behaviour expressed by the single-valued transformation (2.2) or (2.3) will be designated as *combinatorial*, because in this case partial responses are uniquely determined by the corresponding combination of partial stimuli.

The many-valued transformation (2.1) is characterized by the existence of at least one stimulus which is associated with more than one response. In this case we must distinguish two possibilities:

1. *Sequential behaviour*, where different responses of the system to the same stimulus belong to different, but accurately defined sequences of stimuli which preceded the given stimulus.

2. *Random behaviour*, where the transformations (2.1) can be determined only statistically; if the statistical properties of this system do not change during its existence, then it is possible to express this transformation in the form of (2.3), where $\mathbf{f}$ is a probability function.

Sequential and combinatorial behaviour will be referred to by a common designation – *determinate behaviour*. The difference between determinate and random behaviour consists in that determinate behaviour uniquely follows from the structure of the corresponding system, whereas random behaviour can always be expressed only statistically, i.e. even when the structure of the system under consideration is fully known at the given resolution level. Experience shows, however, that the random behaviour of many systems starts to appear determinate as soon as we raise the resolution level when assessing them.

In physical systems there always seems to exist a certain resolution level (expressed by a single node or by several nodes in the resolution graph) for which the behaviour of these systems appears determinate. Of course, the question is whether in some cases the corresponding resolution level is not so high as to be beyond the range of the resolving power of our methods of measurement. In such cases we express the behaviour statistically.

In a sequential system, the response depends not only on the instantaneous stimulus but also on the preceding stimuli. This means, however, that the required stimuli must be remembered by the system in the form of values of some *internal quantities*. Let us term them memory quantities, and the aggregate of their instantaneous values the *internal state* of the system. Its internal state together with the instantaneous stimulus and response will then be regarded as the *state* of the system.

With the aid of the internal state of the system it is possible to formulate an important property of every determinate system: *The response of a determinate system depends always uniquely on its internal state and on the stimulus.*

Let us denote a stimulus applied to a system at time t by the symbol $\mathbf{x}_t$, the corresponding response at time t by the symbol $\mathbf{y}_t$, and the internal state of the system at time t (or $t + \Delta t$) by $\mathbf{s}_t$ (or $\mathbf{s}_{t+\Delta t}$ respectively). We can then express the behaviour of the sequential system in the following general form:

$$\mathbf{y}_t = \mathbf{f}(\mathbf{x}_t, \mathbf{s}_t)$$

$$\mathbf{s}_{t+\Delta t} = \mathbf{g}(\mathbf{x}_t, \mathbf{s}_t)\,,$$

where $\mathbf{f}$ and $\mathbf{g}$ are vector functions.

If, for a certain pair $\mathbf{x}_t$ and $\mathbf{s}_t$,

$$\mathbf{s}_{t+\Delta t} = \mathbf{s}_t ,$$

the system is said to be in a stable state. It remains in this state until the stimulus $\mathbf{x}_t$ changes in a suitable manner. If $\mathbf{s}_{t+\Delta t} \neq \mathbf{s}_t$, the system is in an unstable state, which leads to an autonomous change of the corresponding internal state.

The symbol Δt used in the aforementioned equations defines the time necessary for a change of the internal state, regarded at a given resolution level. If the internal state and the response of the system vary continuously with time, i. e. if $\boldsymbol{f}$ and $\boldsymbol{g}$ are continuous functions and $\Delta t \to 0$, we obtain a special class of systems called continuous (or analogue) systems.

So far we have considered the behaviour of systems independent of time. Hereby we tacitly assumed that the response $\mathbf{y}$ appears at the same

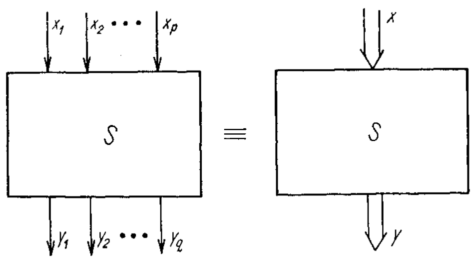

Fig. 2.3. Block diagram of system **S**

instant in time as the corresponding stimulus $\mathbf{x}$. Actually, however, behaviour always proceeds in time, with a certain time lag existing between the stimulus and the corresponding response. This time lag is referred to as the reaction time.

When introducing the time component into our considerations on the behaviour of systems, we must necessarily distinguish two types of behaviour from this aspect:

1. *Discontinuous (discrete) behaviour*, where the states of the vectors $\mathbf{x}$ and $\mathbf{y}$ vary discontinuously with time.

2. *Continuous behaviour*, where the states of the vectors $\mathbf{x}$ and $\mathbf{y}$ vary (at the corresponding resolution level) continuously with time.

In Chapter 4 we shall return to the relation between discrete and continuous behaviour and to other properties of behaviour. There we shall study these problems already in relation to cybernetic systems. Even at the present stage we should remember, however, that the distinction between discrete and continuous behaviour depends on the resolution level (see Sec. 2.3) and is therefore by no means absolute.

Systems are represented in our diagrams by one of the methods shown in Fig. 2.3, according to whether it is necessary to indicate all partial inputs and outputs or whether it is sufficient to show them in vector form only.

2.8 THE ELEMENT

The fundamental part of every system $\mathbf{S}$ is the *element*, which we always regard as a relatively closed system of a lower order with respect to the system $\mathbf{S}$ under investigation.

Every element is characterized by forming, from the point of view of the corresponding resolution level (at which the system $\mathbf{S}$ is defined), an indivisible unit whose structure we either cannot or do not want to resolve. However, if we increase the resolution level in a suitable manner – provided this is possible – the structure of the element can be distinguished. In consequence, the original element loses its meaning and becomes the source of new elements of a relatively different system, i.e. of a system defined at a higher resolution level.

In order to distinguish an element of the system $\mathbf{S}$ from the system proper, it will be denoted by a_i, where the subscript i serves only to distinguish individual elements in the system $\mathbf{S}$. The partial stimuli of the element will be denoted by $v_1, v_2, \ldots, v_l$ (where $l \geqq 1$) and the total stimulus by the vector $\mathbf{v} = (v_1, v_2, \ldots, v_l)$. Similarly, the partial responses of the element will be denoted by $w_1, w_2, \ldots, w_m$ (where $m \geqq 1$) and the total response by the vector $\mathbf{w} = (w_1, w_2, \ldots, w_m)$. The number of partial inputs of element a_i will be denoted by the symbol l_i and in a similar manner the number of partial outputs of element a_i by the symbol m_i. For the stimulus (or response) of element a_i we shall use the notation $\mathbf{v}_i$ (or $\mathbf{w}_i$, respectively), and for its values the notations ${}^1\mathbf{v}_i, {}^2\mathbf{v}_i, \ldots$ (or ${}^1\mathbf{w}_i, {}^2\mathbf{w}_i, \ldots$ respectively).

In block diagrams of systems the elements will be represented by one of the methods shown in Fig. 2.4.

When representing schematically the couplings between the elements of a system in vector form, we shall use the notation given in Fig. 2.5. A coupling between the elements a_i and a_j, oriented from element a_i

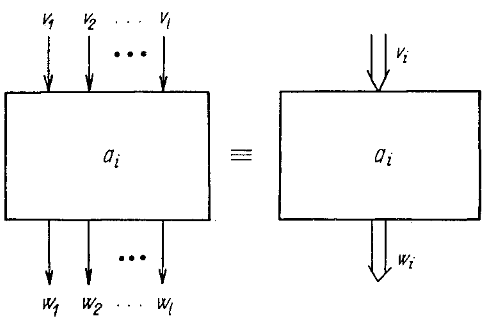

Fig. 2.4. Block diagram of element a_i

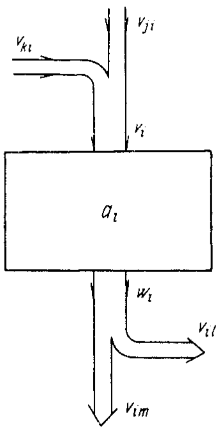

Fig. 2.5. Method of indicating couplings between elements

towards element a_j, will by denoted by the vector $\mathbf{v}_{ij}$, a coupling between the same elements oriented in the opposite direction by $\mathbf{v}_{ji}$. The non-zero couplings $\mathbf{v}_{ji}$ can be regarded as common components of the output vector $\mathbf{w}_j$ and the input vector $\mathbf{v}_i$, where

$$\mathbf{v}_i = (\mathbf{v}_{oi}, \mathbf{v}_{1i}, \ldots, \mathbf{v}_{ni}) \,. \tag{2.4}$$

In determinate systems we must always presume that every partial input of any element is connected with only one out of all the possible partial outputs. This restriction does not apply to partial outputs, i.e. a partial output may be connected with several partial inputs. In such a case the corresponding partial inputs are said to be joined to a common node.

Everything that has been said about the behaviour of a system applies without any change to the behaviour of the element. In general, the be-

haviour of an element a_i is thus expressed by the transformation $\boldsymbol{T}_i$ of vector $\boldsymbol{v}$ into vector $\boldsymbol{w}$, i. e.

$$\boldsymbol{w}_i = \boldsymbol{T}_i(\boldsymbol{v}_i) \tag{2.5}$$

This transformation may acquire different forms, as in the case of a system.

The couplings $\boldsymbol{v}_{ij}$ between the elements must not be confused with the elements $\boldsymbol{r}_{ij}$ of the characteristic of a system. Every $\boldsymbol{r}_{ij}$ defines the dependence of the stimuli of element a_j on the responses of element a_i, whereas the couplings $\boldsymbol{v}_{ij}$ define the common components of vector $\boldsymbol{w}_i$ and $\boldsymbol{v}_j$. Thus, if $\boldsymbol{r}_{ij} \neq 0$, there need be no coupling between the elements a_i and a_j. The dependence $\boldsymbol{r}_{ij}$, may be realized via other (intermediary) elements. If, however, $\boldsymbol{v}_{ij} \neq 0$, there must necessarily also exist a dependence $\boldsymbol{r}_{ij} \neq 0$ between the corresponding elements. Conversely, if $\boldsymbol{r}_{ij} = 0$, then, of necessity, $\boldsymbol{v}_{ij} = 0$.

2.9 Fundamental Couplings

Before proceeding to the explanation of the structure of a system, let us first consider the fundamental methods of couplings between two elements a_i and a_j.

The fundamental types of coupling are illustrated in Figs. 2.6 to 2.8. They are:

1. *Series coupling*,
2. *Parallel coupling*,
3. *Feedback coupling*.

The series coupling of elements a_i and a_j is represented schematically in Fig. 2.6.It is characterized by a part of the vector $\boldsymbol{w}_i$ (denoted $\boldsymbol{v}_{ij}$) forming part of the vector $\boldsymbol{v}_j$. According to the relation between the vector $\boldsymbol{v}_{ij}$ and the vectors $\boldsymbol{w}_i$ and $\boldsymbol{v}_j$ we get altogether four different cases:

a) loose coupling: $\boldsymbol{v}_{ij} \neq \boldsymbol{w}_i$, $\boldsymbol{v}_{ij} \neq \boldsymbol{v}_j$,
b) coupling with loose input: $\boldsymbol{v}_{ij} = \boldsymbol{w}_i$, $\boldsymbol{v}_{ij} \neq \boldsymbol{v}_j$,
c) coupling with loose output: $\boldsymbol{v}_{ij} \neq \boldsymbol{w}_i$, $\boldsymbol{v}_{ij} = \boldsymbol{v}_j$,
d) tight coupling: $\boldsymbol{v}_{ij} = \boldsymbol{w}_i$, $\boldsymbol{v}_{ij} = \boldsymbol{v}_j$.

The schematic diagram of a *parallel coupling* between elements a and a_j is shown in Fig. 2.7. This type of coupling is characterized by the input vectors $\mathbf{v}_i$ and $\mathbf{v}_j$ containing parts (denoted $\mathbf{v}_{ki}$ and $\mathbf{v}_{kj}$) of the output vector $\mathbf{w}_k$ of some third element a_k. According to the relation between the vectors $\mathbf{v}_{ki}$ and $\mathbf{v}_{kj}$ there exist two basic possibilities:

a) unbalanced coupling: $\mathbf{v}_{ki} \neq \mathbf{v}_{kj}$,
b) balanced coupling: $\mathbf{v}_{ki} = \mathbf{v}_{kj}$.

Feedback concerns a single element, for instance a_i. It is characterized by the input vector $\mathbf{v}_i$ of element a_i having a part $\mathbf{v}_{ii}$ in common with the output vector $\mathbf{w}_i$ of this element. In a reduced determinate system

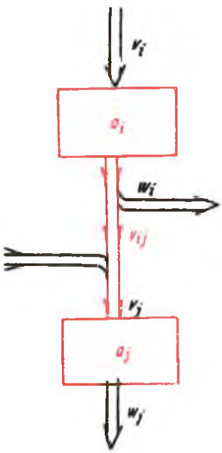

Fig. 2.6. Series coupling

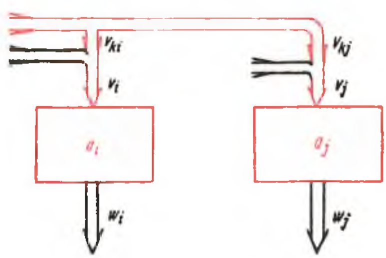

Fig. 2.7. Parallel coupling

we always necessarily have $\mathbf{v}_{ii} \neq \mathbf{v}_i \neq \mathbf{w}_i$, since otherwise the element a_i could not be joined to the remaining elements of the system. A schematic diagram of feedback is given in Fig. 2.8.

More complicated couplings between two elements can be obtained by combining the fundamental types of coupling. If zero coupling — where there is no connection whatever between the elements a_i and a_j — is also taken into consideration, then there exist 18 types of coupling between two elements of a system. They all are tabulated in Fig. 2.9.

Series-parallel coupling (types 13, 14 and 15) occurs when there is simultaneous series and parallel coupling between two elements. It should be noted that in determinate systems the series coupling may in this case be either loose or have a loose input. No other cases are possible, since the element a_j obtains its input not only from the series, but also from the parallel coupling.

If, in some type of coupling, series coupling occurs together with feedback (types 5, 8, 14 and 17), it cannot be tight in determinate sys-

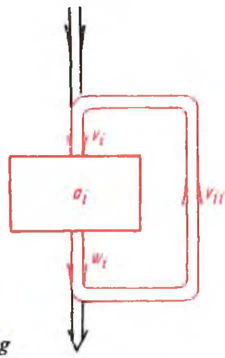

Fig. 2.8. Feedback coupling

tems. When we are concerned with a case featuring two feedback circuits (types 6, 9, 15 and 18), the series coupling must be loose.

Type 7 represents double series coupling. It is characterized, in determinate systems, by the fact that one of the series couplings must always be loose.

The most complicated coupling between two elements occurs in type 18. This comprises two series couplings, one parallel coupling and two feedback couplings. In determinate systems both series couplings in this case are loose.

The coupling $\mathbf{v}_{ij}$ (see Sec. 2.8) between two elements a_i and a_j of a system $\mathbf{S}$ can be expressed in general, for instance, by a matrix having the following properties:

1. It is square.

2. It has m_i (or l_j) rows and columns, if $m_i \geqq l_j$ (or $m_i < l_j$ respectively).

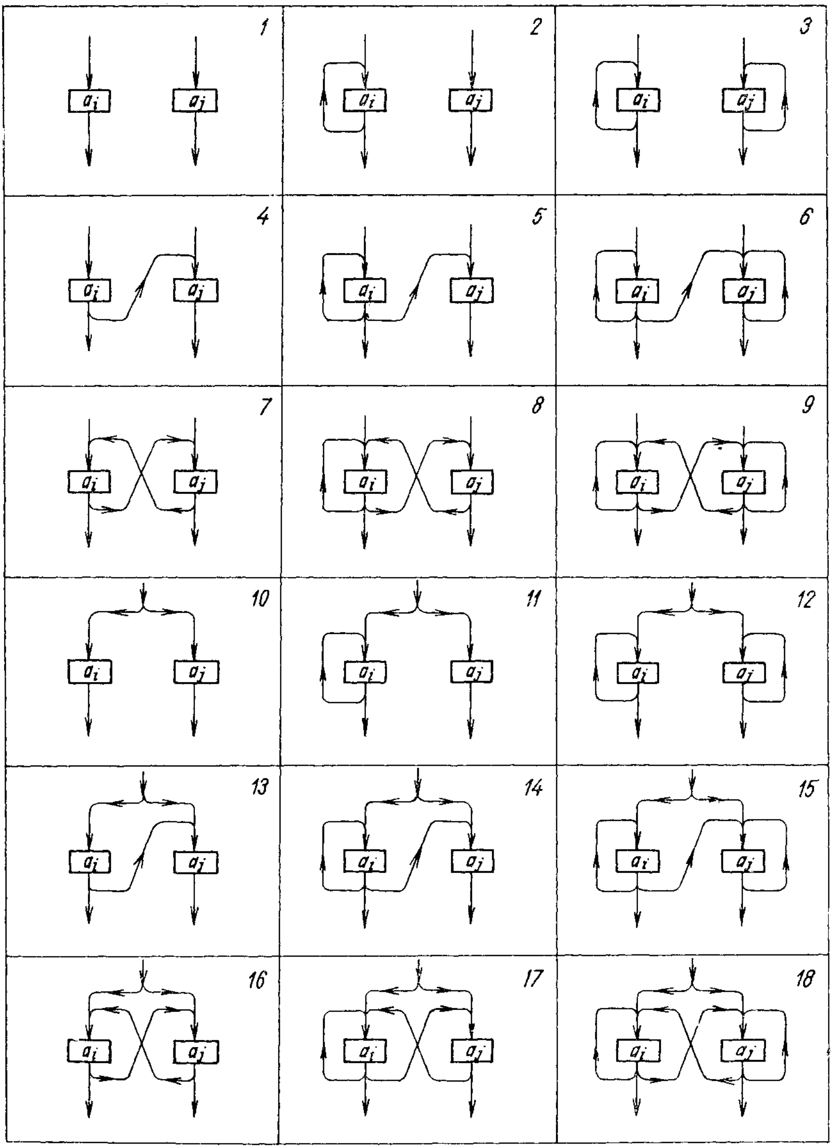

Fig. 2.9. Types of coupling between two elements of a system

3. If the s-th partial output of element a_i is connected with the t-th partial input of element a_j, then the element appertaining to the s-th row and t-th column of the matrix has unity value; if there is no such connection, it has zero value.

In determinate systems the matrix has the following additional properties:

4. There is at least one non-zero element in every column.

5. If $l_j < m_i$, then there are $m_i - l_j$ zero rows; if $m_i < l_j$, then there are $l_j - m_i$ zero columns.

A matrix possessing the properties listed above will be termed the *coupling matrix* and denoted by $\mathbf{w}_{ij}$.

Let us present an example in order to make the properties of the coupling matrix more easily comprehensible. Fig. 2.10 illustrates three elements a_1, a_2 and a_3 which are mutually coupled in a definite manner. For this case, the individual coupling matrices have the following form:

$$\mathbf{w}_{00} = [0], \quad \mathbf{w}_{01} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \quad \mathbf{w}_{02} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{w}_{03} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$\mathbf{w}_{10} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad \mathbf{w}_{11} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad \mathbf{w}_{12} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{w}_{13} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$\mathbf{w}_{20} = [1], \quad \mathbf{w}_{21} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad \mathbf{w}_{22} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{w}_{23} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$\mathbf{w}_{30} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{w}_{31} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{w}_{32} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{w}_{33} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

If a matrix $\mathbf{w}_{ij}$ contains only zeros, it is known as a *zero matrix* and denoted by $\mathbf{w}_{ij} = 0$; in all other cases we shall speak of a non-zero matrix and express it by $\mathbf{w}_{ij} \neq 0$.*)

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*) Since we are not considering the structure of the environment (the element a_0), we shall always assume that $\mathbf{w}_{00} = 0$.

With the aid of the coupling matrices $\mathbf{w}_{ij}$ it is possible to define, for a general system, three basic types of elements from the viewpoint of their inclusion in the structure of the system:

1. a_i is an input element, if $\mathbf{w}_{0i} \neq 0$,
2. a_i is an output element, if $\mathbf{w}_{i0} \neq 0$,
3. a_i is an internal (intermediary) element, if $\mathbf{w}_{0i} = 0$ and $\mathbf{w}_{i0} = 0$.

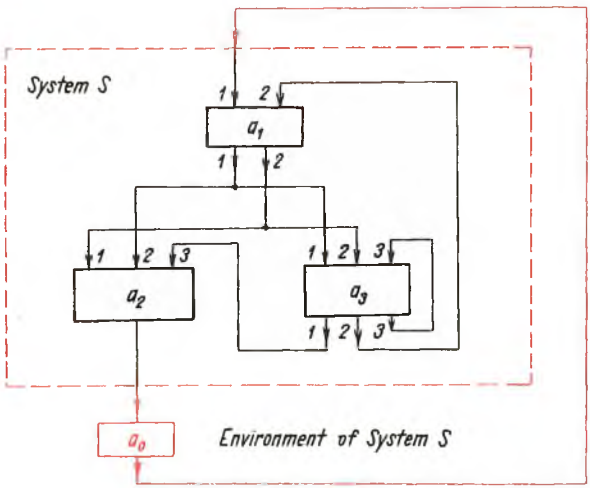

Fig. 2.10. Example of couplings between three elements

2.10 Structure

Let the system $\mathbf{S}$ be composed of n elements denoted by $a_1, a_2, \ldots, a_n$. Let us denote the environment of the system $\mathbf{S}$ by the symbol a_0 (in accordance with Sec. 2.5) and let us consider it as a separate element of this system.

Between every pair of elements a_i and a_j (where $i, j = 0,1, \ldots, n$) there exists either a zero or a non-zero matrix $\mathbf{w}_{ij}$ (see Sec. 2.9). The number of all possible coupling matrices is $(n + 1)^2$.

The structure of the system $\mathbf{S}$ can be described by a matrix $\mathbf{W}$, made

up of the matrices $\mathbf{w}_{ij}$ as follows:

$$\mathbf{W} = \begin{bmatrix} \mathbf{w}_{00} & \mathbf{w}_{01} & \cdots & \mathbf{w}_{0n} \\ \mathbf{w}_{10} & \mathbf{w}_{11} & \cdots & \mathbf{w}_{1n} \\ \cdots & \cdots & \cdots & \cdots \\ \mathbf{w}_{n0} & \mathbf{w}_{n1} & \cdots & \mathbf{w}_{nn} \end{bmatrix} \tag{2.6}$$

The matrix $\mathbf{W}$ will be termed the *structure matrix* of system $\mathbf{S}$. If we substitute either zero (if $\mathbf{w}_{ij} = 0$) or unity (if $\mathbf{w}_{ij} \neq 0$) for the elements $\mathbf{w}_{ij}$ in the structure matrix, the latter will present only a coarse picture of the structure of system $\mathbf{S}$. In this way it is only possible to distinguish mutually coupled pairs of elements from other pairs having no mutual coupling, without regard to the specific peculiarities of the individual couplings. A structure matrix conceived in this sense is denoted by $\mathbf{W}_h$ (coarse structure matrix).

A reduction in resolution level from the viewpoint of system $\mathbf{S}$ manifests itself in that some elements of the system (or their partial inputs or outputs) merge. This leads to a reduction in the number of rows and columns of the corresponding matrix $\mathbf{W}$ (or of the matrices $\mathbf{w}_{ij}$ respectively). In the boundary case the system $\mathbf{S}$ may become the element a_i of some higher system $\mathbf{S}'$.

An increase in resolution level from the viewpoint of system $\mathbf{S}$ manifests itself on the one hand by an increase in the number of elements (due to the structure of some of the original elements being resolved), and on the other hand by an extension in the number of partial inputs or partial outputs of the original elements. The increase in the number of elements leads to a rise in the number of rows and columns of matrix $\mathbf{W}$, an increase in the number of partial inputs or partial outputs of some elements raises the number of rows and columns in the corresponding matrices $\mathbf{w}_{ij}$.

As an example we present the coarse structure matrix of the system shown in Fig. 2.10:

$$\mathbf{W}_h = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 \end{bmatrix}.$$

In this case, the complete structure matrix $\mathbf{W}$ has the form of (2.6), with the matrices listed in Sec. 2.9 substituted for the elements $\mathbf{w}_{ij}$.

2.11 THE NUMBER OF STRUCTURES

Let us again assume that the system **S** consists of n elements, denoted by $a_1, a_2, \ldots, a_n$. The number of possible couplings between the elements (including feedback couplings) is then n^2. If we consider the environment of system **S** as a separate element, the total number of all possible couplings rises to $(n + 1)^2 - 1$.

Now let us see how many different systems can be made up of n elements from the structural point of view. If we first consider the coarse structure only, i. e. if we distinguish only the zero coupling matrices of $\mathbf{v}_{ij}$ from non-zero matrices without taking the peculiarities of the individual couplings into account we can create with the aid of n elements $2^{(n+1)^2-1}$ different systems. However, this number also includes systems not coupled with the environment, i. e. closed systems.

If we want to determine the number of all relatively closed systems, we must first consider the number of all possible structures consisting of n elements without regard to the environment. This number of structures is equal to 2^{n^2}. Owing to the presence of the inputs, the number of possible structures is augmented to $2^{n^2}(2^n - 1)$; the same applies to the influence of the outputs.

From the viewpoint of structure it is thus possible to create $2^{n^2}(2^n - 1)^2 = 2^{n^2+2n} - 2^{n^2+n+1} + 2^{n^2}$ different relatively closed systems, provided that we do not consider the specific peculiarities of the individual couplings between the elements.

In order to obtain a correct idea of the enormous number of systems possible from the viewpoint of structure even for small numbers n, let us again consider the system illustrated in Fig. 2.10, disregarding the couplings shown in it. In this case, the number of possible systems without regard to the peculiarities of the couplings between the elements is equal to 25088.

If we wanted to include in our considerations, in addition, the peculiarities of the couplings between the elements of the system, we would encounter a very exacting combinatorial problem, the general solution of which could probably not be expressed in a sufficiently simple manner. The determination of the number of all possible structures of reduced

systems in the sense of the definition given in Sec. 2.5 would no doubt constitute a still more difficult combinatorial problem.

2.12 Types of Systems

No satisfactory classification of systems has been elaborated so far, since this is a very extensive and, at the same time, a rather difficult matter. The difficulty consists mainly in that the classification of systems can be performed from a large number of different aspects some of which overlap in parts.

We are not going to deal with a complete classification of systems, since the problem is far too wide and is beyond the scope of this book. For a better orientation in the exposition to follow we must, however, take notice of some aspects and of the corresponding classes of systems.

All systems can be divided, first of all, into *physical* and *abstract* ones. The criterion is whether the elements of the system and their interrelations can be physically measured. Systems which are physically measurable will be termed physical systems, all other systems will be known as abstract systems.

Physical and abstract systems formed of a finite universe and a finite characteristic will be termed *limited*, systems with an infinite universe or an infinite characteristic will be named *unlimited*.

If we want to succeed in our study of physical systems, we must confine ourselves to limited systems only. However, this limitation does not apply to abstract systems. The study of unlimited abstract systems may sometimes even be of great importance since some general conclusions or pieces of knowledge which are usable for physical systems may emerge from it.

From the standpoint of their mode of formation, the division of systems into *natural* and *artificial* ones offers itself as a matter of course. Only those systems are considered as artificial, which owe their origin to a conscious impulse of man. All other systems will be considered as natural. Wherever *machines* are mentioned in the subsequent text, they will always be regarded as artificial physical systems.

Every physical system can be assigned to the subject of some branch of science according to the manner in which matter exhibits itself in its

characteristic. The classification of systems from this aspect corresponds therefore to the classification of sciences which will be presented in Sec. 3.6. From the viewpoint of the resolution level, introduced in Sec. 2.3, we shall distinguish:

1. A *complete super-system* – this is a set of all requisite systems defined in an object from a single viewpoint, which differ from each other only by the resolution level of the observer and to which a complete resolution graph is thus assigned (e.g. the set of systems from S_1 to S_5 shown in Fig. 2.2).

2. A *partial super-system* – this is a complete super-system, in which those resolution levels which are inaccessible to the observer are dis-

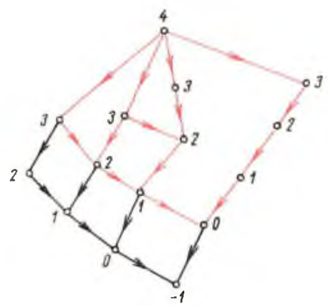

Fig. 2.11. Example of the hierarchy of systems of different order in a resolution graph

regarded. A partial super-system is assigned a part of the complete resolution graph (e.g. the set of systems S_1 and S_2 in Fig. 2.2).

3. A *system* – this is the view from a single resolution level, to which a single node in the resolution graph is assigned (e.g. system S_2 in Fig. 2.2).

From the standpoint of the resolution level we may speak, in some cases, of systems of different order. In such cases we are concerned with systems defined in the same resolution graph, which are characterized by the fact that a system of lower order can be transformed into a system of higher order simply by raising the resolution level. The order of the system is

a relative index relating to some reference resolution level, to which zero is assigned in the given case. The order of a system is raised by unity when we pass over one connecting line in the resolution graph in a direction opposed to the arrow. It is advantageous to choose the reference resolution level (the zero-order system) in such a manner that the orders of the systems in the region which interests us are positive. Systems having different orders with respect to a given reference resolution level can, however, be distinguished in general only in a certain subset of all nodes of the resolution graph.

The resolution graph shown in Fig. 2.11 serves to illustrate the hierarchy of systems of different orders.

The fundamental classification of systems from the standpoint of behaviour has already been dealt with in Sec. 2.7.

2.13 ANALYSIS

The basic types of problem concerning systems have already been briefly mentioned in Sec. 2.6. We shall now continue with their exposition. In this section we are going to direct our attention to the simplest type of problem, i. e. *analysis*.

The analysis of a system is regarded as the determination of its behaviour from its known structure. Speaking of the known structure of a system, we presume the knowledge of:

1. The behaviour of all elements of the system $\mathbf{S}$, i. e. the transformations (2.5) for all values of $i = 1,2,\ldots, n$.

2. The couplings between all pairs of elements including the environment, i. e. the knowledge of the coupling matrices of $\mathbf{v}_{ij}$ for all values of $i, j = 0,1,\ldots, n$.

If we consider the environment of system $\mathbf{S}$ as a separate element and denote it by a_0, we have

$$\mathbf{v}_0 = \mathbf{y}\,, \tag{2.7}$$

$$\mathbf{w}_0 = \mathbf{x}\,, \tag{2.8}$$

where $\mathbf{x}$ is the stimulus and $\mathbf{y}$ the response of system $\mathbf{S}$ (in the sense of Sec. 2.7).

The aim of analysis is then to determine the relation

$$\mathbf{v}_0 = \mathbf{T}_0(\mathbf{w}_0)\,, \tag{2.9}$$

which is identical with the relation (2.1). To achieve this object we may use the relation (2.5) which is known for all values of $i = 1,2,\ldots, n$, and the matrices $\mathbf{w}_{ij}$ which are known for all values of $i, j = 0,1,\ldots, n$.

The matrices $\mathbf{w}_{ij}$ enable us to express the input vectors of individual elements on the basis of the components of the output vectors of other elements. In this we rely on our knowledge of the output vector $\mathbf{w}_0$ of element a_0.

The actual procedure used in our analysis depends to a considerable degree mainly on the type of the relations (2.5) and in part also on the type of the couplings $\mathbf{w}_{ij}$.

2.14 SYNTHESIS

In general, the *synthesis* of a system is every problem which consists in finding at least one structure out of all possible structures which correspond to the given behaviour. Usually, however, the proposed structure is limited by certain restrictions, so that synthesis can be defined more concretely as follows:

1. The behaviour graph is given (see Sec. 2.15) or the behaviour of system **S** is given in some other manner.

2. A limited set of the types of elements is given, the type of element being defined as elements which exhibit the same behaviour.

3. Additional requirements concerning the structure of the system **S** are given, e.g. requirements as to minimum cost, maximum reliability, etc.

4. We are set the task of finding such a structure of system **S**, which would realize the prescribed behaviour and would be composed only of the given types of elements, and which would meet the additional requirements to the optimal degree.

In some instances the synthesis of system **S** may prove impossible. This can be caused either by the fact that the given number of sets of

element types is insufficient, or that the structure is required to meet too exacting additional requirements. In such cases it is necessary to reduce the requirements in a suitable manner or to increase the number of element types.

Synthesis leads sometimes to several different structures. In this case it is possible either to sort out the structures with regard to the fulfilment of some additional requirement, or to select one of them randomly.

We shall acquaint ourselves with the problems concerning the synthesis of systems in greater detail in Chapter 8.

2.15 The Problem of the Black Box

As already mentioned in Sec. 2.6, any system whose structure is not known and is inaccessible to such a degree that it cannot be ascertained by observation is termed a *black box*. The behaviour of the black box is not known either, but it can be observed.

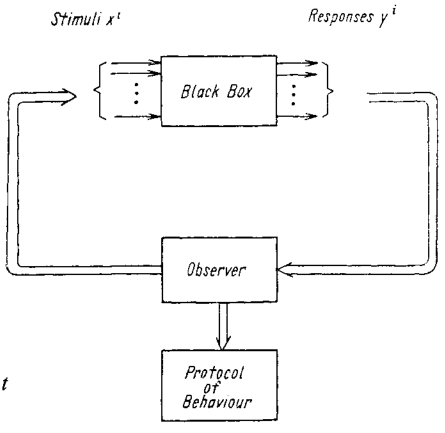

Fig. 2.12. Block diagram of experiment involving a "black box"

The problem of the black box is solved by finding the laws governing the behaviour of the given system and by forming, if possible, a hypothesis of its structure. In this, the observer may act on the system by suitable stimuli and record the corresponding responses (see Fig. 2.12).

The problem of the black box arose originally in electrical engineering, particularly in connection with the theory of electrical networks. For didactic reasons it is sometimes customary to set the task of finding the structure of general n-terminal networks (frequently rather unusual ones) when their behaviour is given. The problem of the black box is met in engineering, however, also for quite practical reasons. This happens, for instance, when a service engineer is faced with the task of discovering a defect in a complicated system (e.g. in a radio or television receiver, motor car, etc.) from its behaviour. In this instance, however, we are concerned with a special case of the problem of the black box, since the service engineer knows the correct structure and behaviour of the given system and wants to ascertain the change in its structure from its deviation from the correct behaviour.

The problem of the black box has, however, a far wider field of application. It turns up typically, for instance, in the determination of medical diagnoses (an analogy to the servicing of engineering systems), when studying diverse biological systems from physiological aspects, in the study of psychological systems, etc.

While the former approach to the solution of the black box problem was purely intuitive and was concerned with special cases, the theory of systems aims at a generalization of this problem and at the creation of a systematic approach to its solution. Many questions relating to the problem of the black box, however, are not yet elucidated.

The manner in which the observer experiments with the black box may be greatly diverse in character, but it must comply with some general conditions:

1. During the experiment the black box must be perfectly isolated in the sense that it cannot be entered by other stimuli (from the standpoint of a certain resolution level) than those considered by the observer. In some systems, of course, e.g. in biological ones, this requirement can be met only approximately.

2. The observer must choose an environment which permits the system of the black box to be suitably stimulated during the experiment.

3. In the course of the experiment the observer must keep a protocol of all stimulus-response pairs in their order of occurrence. In systems

exhibiting continuous behaviour we are concerned in this case with a graphic record of stimuli and responses.

On the basis of the protocol of stimuli and responses (or with the aid of the graphic record) the experimenter may attempt to find the rules governing the behaviour of the system. If we are concerned with a system exhibiting combinatorial behaviour (Sec. 2.7) it will be relatively easy to discover these rules. If the behaviour is sequential, the preparation of the experiment and the analysis of the protocol obtained is far more exacting. Random behaviour can be evaluated only statistically. In the majority of cases, however, the observer studying the black box does not know the type of behaviour of the corresponding system beforehand.

When analysing the protocol – provided we are not concerned with a continuous system (Sec. 2.7) – the most convenient procedure is to express it first by means of an oriented graph*) possessing the following properties:

1. The nodes of the graph correspond to individual states of the system, the connecting lines to changes of stimuli.

2. Different "stimulus-response" pairs are always assigned different nodes in the graph.

3. Different nodes may be assigned to the same "stimulus-response" pairs, but only if there is no doubt that to each pair there belongs a different internal state. This happens if the same "stimulus-response" pair is repeated several times; only then does the same stimulus lead to a changed response.

A graph having the aforesaid properties is termed a *behaviour graph.* On the basis of the behaviour graph we may speak of the *structure of behaviour*, which must in no case be confused with the structure of the system. It is obvious that the structure of behaviour (especially that of sequential behaviour) can be gathered more clearly from the behaviour graph than from the original protocol (since we are concerned with a method of representation that is invariant in time). To illustrate our

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*) An oriented graph is regarded here, similarly as in Sec. 2.4, in the sense of reference [C 3], i. e. as a non-empty set of points combined with a non-empty set of oriented connecting lines between these points.

case we present in Fig. 2.13 a graph of simple combinatorial behaviour and in Fig. 2.14 a graph of simple sequential behaviour. In both cases there occur only three stimuli and three responses. The stimuli are denoted by $^1\mathbf{x}$, $^2\mathbf{x}$, and $^3\mathbf{x}$, the responses by $^1\mathbf{y}$, $^2\mathbf{y}$, and $^3\mathbf{y}$.

It is worth noting that with determinate behaviour (combinatorial and sequential) only a single connecting line starts from any node of the

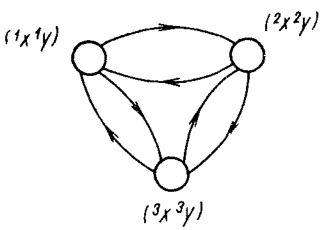

Fig. 2.13. Example of a graph of combinatorial behaviour

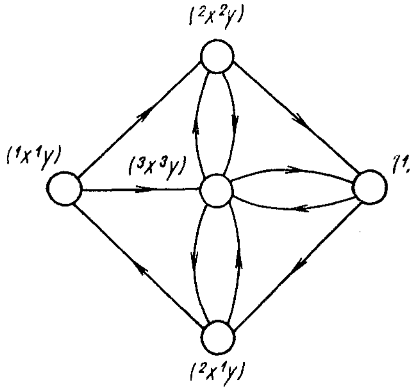

Fig. 2.14. Example of a graph of sequential behaviour

behaviour graph for every stimulus. With random behaviour, there may be several connecting lines going out from a certain node for a single stimulus, a distinct probability being associated with each connecting line.

An example of a graph of simple random behaviour is given in Fig. 2.15. Let us note that the sum of probabilities of all connecting lines going out from a certain node and corresponding to the same stimulus is always equal to unity, since there always occurs some of the alternatives mentioned.

When experimenting with a black box we must constantly keep in mind that we can never fully verify whether the structure of behaviour (the behaviour graph) as ascertained corresponds to reality. For such a confirmation, however, it is sometimes sufficient to know – at least partially – the structure of the corresponding system. Solutions of problems of this kind can be found especially in works concerned with the theory of discrete limited systems [C 16].

Among the most famous instances of successful experimentation with black boxes were I. P. PAVLOV's outstanding experiments on animals, which led to the discovery of conditioned reflexes, had a profound effect on the further progress of neurophysiology and psychology, and

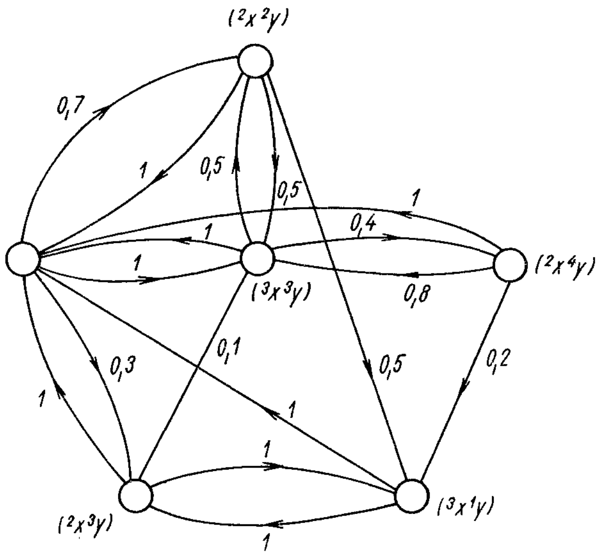

Fig. 2.15. Example of a graph of random behaviour

also had important philosophical consequences. It is worth noting that in the formation of conditioned reflexes we are concerned with a typical sequential behaviour, which appears both at the beginning and at the end of each completed experiment as combinatorial. The problems concerning conditioned reflexes will be dealt with more fully in Chapters 8 and 11.

The problem of the black box has grown extraordinarily in importance in connection with the modelling of the behaviour of biological and psychological systems which are typical black boxes. It is usually impossible to observe the structure of these systems directly; when studying them we must therefore depend on their behaviour. This is why we shall

return to the problem of the black box in a more concrete form in many passages of this book.

Let us note that, when solving black box problems, we start from experiments (i.e. we determine the laws governing behaviour); these are followed by synthesis (the possible structure of the system is determined on the basis of the ascertained behaviour) and finally by analysis (verification whether the presumed structure of the system is in agreement with the behaviour ascertained).

CHAPTER 3

CYBERNETICS

The subject of cybernetics is still a matter of controversy. We presume this state of things to be caused by the lack of attention devoted to the clarification of the basic features of this new science. By this we mean chiefly a sufficiently general and accurate definition of the subject matter of cybernetics, a clear statement of the relation between cybernetics and other scientific disciplines, and the elucidation of the fundamental concepts of cybernetics.

This chapter is devoted to a brief statement of the subject of cybernetics. For the sake of completeness we shall first give a short account of its origin and evolution. In explaining cybernetic concepts we shall here confine ourselves to three basic concepts only: information, signal, and code. Other concepts will be explained, as the need arises, in later chapters.

3.1 ORIGIN AND EVOLUTION OF CYBERNETICS

Cybernetics is one of the youngest scientific disciplines. Its origin is due mainly to the great development in the 20th century of the physical sciences, engineering, and the biological sciences.

Modern engineering offers instruments of increasing perfection to the biological sciences for experimental work (such as electron microscopes, encephalographs, ultrasonic apparatus, and many other devices) which permit the study of processes in living organisms to be pursued with greater accuracy. Thus it has been possible to throw more and more light upon the relation between the behaviour of living organisms and their structure.

While important biological laws were being discovered, methods of organizing inanimate systems were also developed. Systems featuring

increasingly complicated patterns of behaviour have been made up of physical elements provided by modern technology (linkages and other mechanisms, relays, electronic valves, ferrite components, semiconductor devices, etc.). Mathematics has contributed to this development chiefly by evolving methods of synthesis (synthesis of bar-linkages, synthesis of switching circuits, synthesis of electrical four-terminal networks, etc.) which have permitted systems possessing the required behaviour to be designed from the physical elements available.

The study of methods for organizing inanimate systems began to develop with extraordinary speed during the 2nd World War, and especially after it, in connection with the newly emerging branch of data processing machines. The first universal mathematical machines – automatic computers – and other complicated technical systems were built, which in many respects resembled the behaviour of living organisms. Thus, in many cases the behaviour of animate and inanimate systems turned out to be analogous. It appeared, for instance, that some organs of the human body (heart, kidneys, and others) could be temporarily replaced by artificial (inanimate) systems. These facts necessarily led to the conclusion that other properties of the two classes of systems, which determine their behaviour, are also analogous. It proved impossible, however, to fit the study of some of these properties into any existing branch of science. Therefore it was felt that a new aspect should be introduced for defining systems in physical objects.

The introduction of this new viewpoint, which is closely connected with the concept of *information* (see Sec. 3.2), proved so useful to the further and more profound study of some objects, that at a certain stage in the development of science it appeared expedient to establish a new scientific discipline for it – namely *cybernetics.*

The rise of cybernetics was thus conditioned by a certain stage in the evolution of science. The actual foundations of cybernetics were laid, however, by the outstanding American mathematician NORBERT WIENER (1894–1964) in 1948 in his book "*Cybernetics*" [A31]. WIENER is also the author of the name "*cybernetics*" itself, which he took from the Greek where "*kybernetes*" means "steersman". It is known from history that the same term was already used in antiquity by the Greek philosopher Plato to designate "the science of the steering of ships". The same

term was again used later, in about 1843, by the French mathematician, physicist and philosopher AMPERE for "the science of the control of society". NORBERT WIENER was thus the third to use this term, this time for the science intended to deal with *control in machines as well as in animate systems.*

The evolution leading to the emergence of cybernetics was very fast. This is why its essential traits were not fully staked out at the very beginning. It was therefore possible to comprehend its meaning in different ways. At first this resulted in sharp ideological controversies involving cybernetics. As the papers dealing with cybernetics grew in number, it was increasingly looked upon with greater understanding and this led to a gradual abatement of the controversy. Since about 1955 cybernetics has been generally adopted as a new fundamental scientific discipline, although there are some workers in this field who are still opposed to it. We may assume this opposition to be caused in the majority of cases either by a narrow view of the subject and methods of cybernetics, or by a certain disappointment resulting from the fact that cybernetics has so far been unable to help in solving certain specific problems of some other branches of science.

Cybernetics is still at the beginning of its evolution. If we compare its development, for instance, with that of chemistry, it is at about the stage chemistry was at the times of LAVOISIER (at the end of the 18th century) when it stopped occupying itself with alchemical speculations and began to devote itself to accurate experimental work, and when some fundamental chemical laws were discovered.

In spite of this, cybernetics has during its short existence already yielded remarkable results and influenced the development of many other scientific disciplines. Thus, in biology for instance, cybernetics has led to a deeper insight into some functions of living organisms (sense organs, neurohumoral control mechanisms). Cybernetics has also contributed to the emergence of many new hypotheses concerning the explanation of functions not fully investigated so far (the theory of memory, the function of the neuron and of neuron networks, coding of information in the germ cell, etc.). Some newly evolved branches of mathematics were deeply affected by cybernetics, e.g. information theory, the theory of automata, the theory of games, etc. On the other hand, engineering

utilizes new principles yielded by cybernetics. Among these are, for instance, new methods for the communication of information, systems with goal-seeking behaviour based on experience, self-organizing systems, and many other principles. Cybernetics is also related to philosophy in the sense that it helps to clarify ideas concerning the relation between animate and inanimate matter.

3.2 INFORMATION

The concept of *information* may be considered as the central concept in the entire field of cybernetics. Any phenomenon forming the subject of cybernetics is always connected in some manner with information, even though this connection is not always obvious. The relation of cybernetics to the information concept is therefore similar, for instance, to the relation of mathematics to the number concept, the relation of power engineering to the energy concept, the relation of hydraulics to the concept of liquids, etc.

In the sense the word is used in cybernetics, information is a certain quantity which in some cases can vary continuously, i.e. its value can be expressed in such cases only by non-cardinal numbers, irrational numbers, etc.

The information concept has a far wider meaning in cybernetics than is assigned to it in ordinary life. Not only news items and data in newspapers, other periodicals, railway guides, telephone directories, radio broadcasts, etc. are considered as carriers of information, but included are also, for instance, signals received by any animal through its sense organs or receptors, electrical impulses passing from the receptors over nerve fibres to the brain, and from the brain, for instance, to muscles, the initial values in a given mathematical problem, as well as different intermediate values and final values representing the solution of the given problem, pulses transmitted by the dial of a telephone set and received by the equipment of an automatic exchange, etc.

In the most general sense, information may be regarded as the *measure of the amount of organization* (as opposed to randomness). However, the relation between the amount of information and organization is in gen-

eral very complicated and has as yet not been investigated from all desirable aspects. The difficulty consists mainly in that the amount of information depends not only on the quantity of organization, but also on its quality. This is because the amount of information can frequently be determined only with respect to a certain system, according to the reduction of uncertainty in the behaviour of the given system due to the organization of another system.

An illustration of the above statement is provided, for instance, by a card index of scientific periodicals. A card index consisting of blank cards offers no information at all. A card index with correctly completed cards presents, for instance, information as to which periodicals can be borrowed from the library. If the cards in the card index are arranged in some manner, then the index also presents information on how to make sure in the quickest possible manner, whether a certain periodical is in the library. The amount of this information depends on the arrangement of the cards in the index. In this case, however, it not only depends on the "depth" of the arrangement (the number of the first letters of individual words according to which the cards are arranged), but also on its manner (e.g. on the order of letters selected, etc.). The better the user of the card index knows the given method of arrangement, the larger the amount of information, and vice versa.

It should be noted that, in the example given above, we related the organization of one system (the card index) to that of another system (a certain region in the central nervous system of the user of the card index). In this case the organization of one system constituted information for the other system. It appears that the amount of information is given not only by the quantity of organization of the two systems considered separately, but to an appreciable degree depends on the mutual relation between the arrangements of the two systems. We shall return to this problem in Chapter 13.

The example of the card index served to illustrate one of the possible approaches to the assessment of the amount of information, sometimes called the *semantic viewpoint*. This is quite a general viewpoint, but rather exacting as to its precise elaboration. Therefore, a simplified approach was found to the problem of expressing the amount of information, particularly for practical purposes concerned with the needs of cybernetic

engineering systems. This approach relies only on the quantitative aspect of organization, as though tacitly assuming that the correct manner of organization were guaranteed in advance. This assumption is always satisfied in engineering systems, since it is the duty of the designer to ensure that it is fulfilled in every device he constructs.

As an example let us take a radio communication system utilizing speech transmission. If the transmitter of this system employs amplitude modulation with a carrier frequency of 1 Mc/s, its receiver must be arranged so as to be capable of receiving electromagnetic waves at a frequency of 1 Mc/s, provide facilities for amplitude demodulation and for the conversion of the demodulated signal to sound waves of sufficient intensity. The organization of the receiver must thus be related in a certain manner to the organization of the transmitter to ensure that the communication system have a meaning. If the corresponding relation were not satisfied, the arriving modulated electromagnetic waves would not constitute any information in the semantic sense with respect to the receiver.

The relations required to exist between the amounts of organization in individual parts of engineering systems are usually so much a matter of course, that the designer of the system under consideration hardly realizes that he is incorporating them in his design. The designer of engineering systems therefore usually aims directly at achieving the functions required of the individual parts of the equipment by a suitable arrangement of its components.

This simplified aspect of information, which is of considerable importance to the study of cybernetic engineering systems, has become the basis of a branch of cybernetic known as *information theory*. This owes its origin mainly to the American mathematician and engineer C. E. SHANNON [C 33].

Information theory regards information as a quantity analogous to entropy (expressed by the same relation as entropy), but considered in such a manner that an increase of information corresponds to a decrease of entropy, and vice versa.

The concept of *entropy* is borrowed from thermodynamics, where it is used to express the possibility of discrimination between or the amount of randomness in the states of some physical systems. In thermodynam-

ics, an increase of entropy corresponds to the transition from a more highly organized state of the physical system to a less organized state, this transition being always accompanied by a release of energy (e.g., atomic energy is released when the organization of the atomic nucleus is disturbed). A decrease of entropy corresponds to the converse transition, in which a certain amount of energy is always consumed (e.g. chemical synthesis, exemplified by the production of large molecules, always consumes energy).

As used in information theory, entropy has no relation to its established use in physics, and an abstract, statistical definition is introduced for it. If, out of n events, each can occur with the probabilities $p_1, p_2, \ldots, p_n$, where $\sum_{i=1}^{n} p_i = 1$ (i.e. some of the given events are bound to occur), then the expression

$$H = -\sum_{i=1}^{n} p_i \log_a p_i$$

is called entropy.

It would be easy to ascertain that entropy defined in this manner is never negative (its minimum value is zero) and that it is largest when all the probabilities p_i are equal, i.e. when $p_i = 1/n$ for all values of $i = 1, 2, \ldots, n$. In such a case we are concerned with totally unorganized events, the complete discrimination of which requires the maximum amount of information. In general, the complete organization (or discrimination) of certain events requires an amount of information exactly equal to their entropy. For maximum entropy we obtain $H_{\max} = \log_a n$.

The reasons for using the logarithmic function in the definition of entropy are explained in books dealing with information theory [A15].

The unit used for measuring entropy and thus also that for measuring the amount of information is defined by the choice of the base of the logarithms employed to express the entropy.

It is advantageous to use logarithms to the base 2 ($a = 2$). Then the unit measure of the amount of information will be the smallest possible quantum of information. This smallest amount of information is obtained in general by getting the answer "yes" or "no" to a suitable question.

The name adopted for the unit of information derived from logarithms to the base 2 is the "*bit*". This designation is made up artificially of the two initial letters and the final letter of the term "*binary digit*".

The definition of entropy and thus also that of the amount of information can be extended to cover the continuous probability function $p(x)$, if addition is replaced by integration:

$$H = -\int_{-\infty}^{\infty} p(x) \log_a p(x) \, dx.$$

We might consider the probability functions of several variables in a similar manner. However, it is not our task to deal with information theory. The preceding explanation has been included in this section only to indicate in what manner the information concept is regarded in cybernetics. For a more profound study of the problems concerned with information the reader is referred to some monographs listed in the bibliography [A5, A7, A15].

We shall return to the information concept in Chapter 13 in connection with the concept of the proper model of a system.

3.3 The Signal

The discussion in the preceding section has shown that – according to the terminology of information theory – information is an abstract concept used to express the degree of organization of some system from different viewpoints. In this respect it is essential that information is not of a physical nature. At the same time, however, it is important to realize that information can be considered only in connection with matter. If there were no matter, there would be no organization either and the information concept would have no sense whatever.

This statement might be objected to on the ground that we might create organization in our imagination without considering the organization of a physical system. As an example we may quote idealized abstract imaginary geometrical conceptions. It is easy to show, however, that even in this case the physical system is a condition of organization,

and thus also of the existence of information. This is because imagination itself depends on a certain organization of the nervous system. Without this material foundation, there would exist neither imagination nor the organization contained in it.

The existence of information thus depends on the existence of matter. In this context, the information concept is closely linked with the *signal concept.* In general, this is the material foundation carrying the information, i.e. it may be represented by any organized matter. The amount of information in the signal is given here not only by the absolute organization of the physical system forming the given signal, but also by the resolution used to assess the signal.

An *elementary signal* is defined as a physical system which, from the standpoint of the resolution level applied, is in one of two possible states. To such a signal we assign the elementary unit of information (in the sense of the technical point of view), i.e. 1 bit.

Signals can be *static* or *dynamic.* In static signals we are concerned with spatial organization only, in dynamic signals the time component in also manifest.

With the aid of the information and signal concepts we can now outline some further concepts.

A given system is said to *receive information* when its environment acts on the system with such stimuli which increase its organization. A necessary condition enabling information to be received is that the stimuli be expressed by signals. However, every system is capable of directly receiving some types of signal only (it is selective to the reception of signals), and it can receive these signals only at a given resolution level. Man, for instance, is unable so perceive ultrasonic signals directly (they are beyond his "frequency response"), neither can he directly receive signals at molecular level (his power of resolution is limited).

If, on arrival of a signal at the input of the system, the organization of the system changes and remains changed even when the signal no longer acts upon it, the system is said to have remembered the information contained in the signal (*information storage* occurred in the system).

If, in the system, changes occur in the organization, *information processing* is said to have taken place in the system. If the partial organization in the system is displaced without any change, we speak

of information transfer inside the system. If the system transfers part of its organization to the environment, or vice versa, we are concerned with *control.*

3.4 CODES

If we compare information and signal, we find that the same information can be expressed by various signals and, conversely, various meanings can be attributed to a given signal. In order to ensure that signals have the meaning of the information, there must exist a set of rules according to which a certain informational meaning is assigned to individual signals. A set of such rules is called a code. To be more accurate: a *code* is a set of rules prescribing how a certain signal is to be uniquely assigned to a given informational meaning.

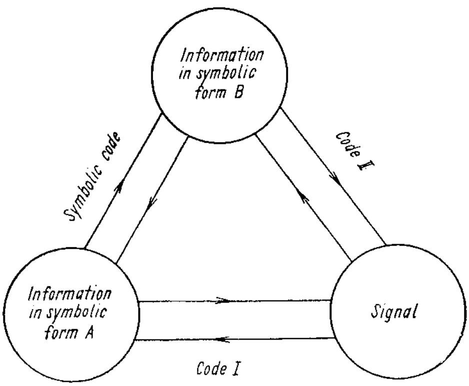

Fig. 3.1. Relations between fundamental concepts

Information can be expressed by various sets of abstract symbols (e.g. by digits of some number representation). A prescription according to which information in one symbolic form is uniquely represented by some other symbolic form will be called a *symbolic code.*

The concepts introduced here in connection with the coding of information are clearly shown in Fig. 3.1.

In general, two types of code can be distinguished: analogue and digital. *Analogue codes* represent continuously variable information by

continuously variable physical quantities. As an example we quote the height of the mercury column in the thermometer, which carries information on the magnitude of the temperature. *Digital codes* represent information changing in finite steps by discrete states of physical parameters. An example is provided by the keyboard of a desk calculator. The division into analogue and digital codes is very important and is one of the viewpoints for the classification of systems (see Chapter 4).

3.5 The Definition of Cybernetics

In his classical book [A31], Norbert Wiener defined cybernetics as "*the science of control and communication in the animal and the machine*". This definition is inseparably associated with the origin of cybernetics. It seems that in it Wiener endeavoured to emphasize the fact that cybernetics is concerned not only with engineering systems but that it also deals, from the standpoint of control and communication, with systems defined in living organisms.

The definition of any scientific discipline should briefly, but accurately and expressively state the range of phenomena which form the subject of study in the given field. Wiener's definition delimits the phenomena forming the subject of cybernetics in two respects:

1. It determines the types of object for which it is possible to define the systems that form the subject of interest to cybernetics: animals and machines.

2. It states the points of view from which these systems are to be defined for the given objects: control and communication.

The evolution of cybernetics has shown that Wiener's definition restricts the actual subject of cybernetics in both respects in an undesirable manner. The statement of the cybernetic system in Wiener's definition is unsuitable particularly because the viewpoints of control and communication can be applied theoretically to any object and used to define a system for the object. For instance, it does not include economic and social objects in which control and communication fully assert themselves, and which are now from this standpoint rightly included in the field of cybernetics. Neither does Wiener's definition take any account

of abstract systems, such as mathematical and linguistic systems, to which some cybernetic laws also apply. As far as physical systems are concerned, Wiener's definition confines itself to machines, i.e. to objects created by man for some purposeful activity.

As far as the statement of the viewpoint is concerned, Wiener's definition is also somewhat incomplete. It considers only two processes associated with information, i.e. communication and control. There is, however, a greater number of such processes (e.g. information storage, information processing, etc.); each of these processes, which is immediately concerned with information, obviously pertains to cybernetics and cannot very well be included in any other branch of science.

These deficiencies in Wiener's original definition led to the search for a new, more general and more comprehensive definition. Up to the present a great number of various alternative definitions have been suggested, but none of them has so far found general acceptance. It will therefore be certainly useful and interesting to sum up the principal definitions known and to attempt, with their aid, to arrive at a definition which would be as general as possible, sufficiently expressive, and as brief as possible.

The definitions of cybernetics can be classified under several headings. The first class comprises definitions which in various ways modify Wiener's original definition. These can be subdivided into three groups, characterized by the following three definitions typical of them:

1. *Cybernetics is a science which studies control systems and processes by mathematical methods.*

2. *Cybernetics is the science of the processes of transmission, processing and storage of information.*

3. *Cybernetics is a science which studies the methods of the forming, structure and transformation of algorithms describing processes of control that occur in reality.*

The reader will be certainly interested to be informed of some differently formulated definitions of cybernetics which can be included in the first class:

"*Cybernetics is the science of the laws of control of complex dynamic systems*" (A. I. Berg [C 2]).

"*Cybernetics is a science which investigates the laws governing the useful activity of automata and living beings*" (V. DROZEN, see the preface to the Czech edition of Ref. [A5]).

"*Cybernetics is the science of the quantitative and structural laws governing control systems*" (A. KOLMAN [B37]).

"*Cybernetics deals with the study of systems of arbitrary character, capable of receiving, storing and processing information and utilizing it for purposes of control and regulation*" (A. N. KOLMOGOROV, preface to the Russion edition of Ref. [A1]).

"*Cybernetics is a science which investigates, from a single general point of view, the problems of the control of various processes in different systems and the transfer or communication of control signals within these systems or between them*" (J. KLÍR [C22]).

"*Cybernetics is the science of control in machines, living organisms and societes and of the transmission of signals within them*" (I. A. POLETAEV [A26]).

"*Cybernetics studies, in an abstract form, the properties and laws of behaviour in various systems of control, independently of the physical nature of these systems*" (S. M. SHALYUTIN [A11]).

The second class may be said to include definitions based on the general concept of the system and on the information concept:

"*Cybernetics might be defined as the study of systems that are open to energy but closed to information and control — systems that are "information-tight*" (W. R. ASHBY [A1]).

"*Cybernetics is the general science of informed, informing and, particularly, of information systems*" (H. GRENIEWSKI [A16]).

A representative of the third, highly original class is L. COUFFIGNAL, who in Ref. [A10] tries to prove that cybernetics belongs to that field of human activity which we call "art". In his opinion we are here concerned with *the art of how to approach the solution of various problems, in other words how to act under various circumstances.* In the Soviet Union, a similar attitude is taken by I. B. NOVIK, who defines cybernetics as *the science of the optimization of activity*, implying only activities that have not yet been fully investigated.

The views of A. A. MARKOV [C25] can be included in the fourth class. According to this author, cybernetics is *the general theory of causal nets*,

which studies them with an accuracy reaching as far as isomorphy. A slightly narrower but essentially similar view is held by G. KLAUS [A20] who defines cybernetics as *the theory of relations between possible dynamic regulating systems and their partial systems.*

A representative of the last class is A. SVOBODA, who defines cybernetics as a *methodical approach to the study of limited systems (i.e. sets of space-time quantities considered as a single whole) that exhibit a specific behaviour considered as the statistically defined relation between the stimuli by which the environment acts on the system, and the responses by which the system affects its environment.*

Of all the definitions listed we consider those included in the second class to be the most expressive. They describe, by their informational point of view applied to general systems, the real nature of cybernetics very well and in the most general manner. Besides, they do not contradict Wiener's original definition. We also consider A. Svoboda's definition to be highly expressive and, to an appreciable degree, also general; in our opinion its only disadvantage consists in that it does not state more closely the standpoint in which the corresponding methodical approach consists.

The other definitions seem to us less expressive. The most general definition of the first class is that of Kolmogorov, but even this contains a certain restriction in that the viewpoint stated is not necessarily exhaustive. The definitions of the third class are not in agreement with Wiener's original definition, i.e. they do not fully express the subjects of this definition. The viewpoint stated in them is not characteristic of cybernetics but applies more or less to every science.

Markov's definition is, first of all, far too general since causal nets are dealt with by other sciences as well, e.g. by mathematics, logic, philosophy, etc. On the other hand, not all the phenomena included in Wiener's definition can be expressed by the theory of causal nets. For instance, we are not concerned with causal relations when comparing the information-handling capacities of different communication channels. This, however, is a fundamental concern of cybernetics, which cannot very well be included in any other fundamental scientific discipline. In a certain sense, Markov's definition thus represents a restriction of Wiener's definition.

The deficiency of the definition given by Klaus consists primarily in that it does state more accurately the type of relations dealt with by cybernetics. It is obvious, of course, that cybernetics is not concerned with energy relations, even though such relations no doubt occur in dynamic regulating systems. Moreover, Klaus's definition restricts the subject of cybernetics by confining itself to dynamic regulating systems. Cybernetics is, however, also interested in problems not concerned with dynamic regulating systems, for instance with the problem of communication systems, coding of information, etc.

Thus, in our opinion, the most acceptable definitions are those comprising the second class, and Svoboda's definition. If we try to combine all positive aspects of the definitions quoted, and apply the concepts already introduced in this book, we arrive at a definition of the following type:

Cybernetics is a science dealing, on the one hand, with the study of relatively closed systems from the viewpoint of their interchange of information with their environment, on the other hand with the study of the structures of these systems from the viewpoint of the information interchange between their elements.

3.6 A Survey of Science and the Place of Cybernetics

The task of science in a wider sense is the truthful cognition of the world.

In principle, science starts from the assumption that the world is indivisible in the sense that all phenomena in it are mutually dependent, even though their relations are not always sufficiently obvious. It is the aim of science to discover the corresponding relations and to prove them objectively.

If the world is indivisible, the process of cognition should also be indivisible, and thus there should exist only a single science. This, however, was possible only at a primitive stage of cognition, when the relations between individual phenomena were known only very superficially. At that time there really existed only a single science – philosophy – which encompassed all the knowledge of that time. As the amount of

knowledge in philosophy gradually accumulated, an ever greater effort was needed to comprehend and elaborate it. An unavoidable result was the splitting of science into special branches, i. e. the introduction of the division of labour into science. Actually, this process cannot be considered as a division in the proper sense of the word, but as the process of distinguishing some new branches of science from philosophy, whose existence remained unaffected.

Natural science (at that time called physics) was separated from philosophy already in antiquity. At that time, the principal concerns of natural science were mathematics and astronomy.

A further division of science did not take place until the beginning of modern times (in the 15th and 16th centuries) when mathematics and physics were introduced as independent subjects, the latter being considered chiefly as mechanics (I. NEWTON). In the 18th century the scientific foundations were laid of chemistry (A. LAVOISIER and M. V. LOMONOSOV) and partly of biology (K. LINNÉ). Some special branches of physics also emerged, in particular mechanics and heat.

A great development of science took place in the 19th century, when the sciences concerned with inanimate nature became clearly separated from biology. Biology was put on a scientific footing, chiefly by the cell theory of J. EV. PURKYNĚ and the evolution theory of C. DARWIN. Chemistry was divided into inorganic and organic chemistry, and a number of new branches appeared in mathematics and physics. The 19th century is also characterized by the evolution of the engineering sciences, especially mechanical engineering, and by the emergence of new human sciences (e.g. psychology, sociology, etc.).

Our century is marked by a still more rapid development of science. Fundamental scientific disciplines, such as mathematics and biology, are already subdivided into a great many special branches and new divisions are constantly appearing. In addition, some entirely new scientific disciplines emerged in the 20th century, such as astronautics, nuclear engineering, cybernetics, eugenics, semiotics, bionics, sociometry, and others. Orientation in science is thus getting increasingly difficult, the more so because there is an absolute lack of literature dealing with the general classification of sciences or classification within the framework of individual special sciences.

Every scientific discipline studies the relations within the framework of a specific class of phenomena, which exhibit properties common from a given point of view and which form the subject of the scientific discipline under consideration. The precise statement of the subject of individual scientific disciplines is given by their definitions. The contents of a particular scientific discipline are considered to consist, on the one hand, of a well-ordered collection of all items of knowledge concerning its subject, and on the other hand of a set of methodical resources enabling us to obtain further knowledge.

However, philosophy has lost nothing of its importance even after the division of science into separate branches. Its main task consists in gathering, in a condensed form, all human knowledge dispersed in the individual sciences. Thereby it preserves a unified view of the world and thus creates a unified and consistent conception of the world.

Philosophy draws upon the findings of the other sciences and, based on them, it formulates hypotheses of the most general laws governing the evolution of nature and of human society. Conversely, philosophical hypotheses aid the individual sciences in choosing suitable methods of scientific research.

The tasks of philosophy also include the dividing of science into scientific disciplines. A correct division presupposes that, at a certain stage in the development of science, the corresponding system of scientific disciplines is complete and natural and thus forms a kind of "map" of our knowledge. In this sense, philosophy should exert its actual influence on this map, i.e. it should progressively adapt and supplement it.

Philosophy, as described, thus occupies a special position among the sciences. The other sciences can be divided roughly into mathematics, natural, human and engineering sciences. Within each of these classes we must distinguish fundamental from special sciences.

The fundamental natural sciences are physics, chemistry and biology. The fundamental human sciences can be taken to include psychology, linguistics, sociology, history, political economics, etc. Among the engineering sciences let us mention, for instance, power engineering, chemical technology, communications engineering, and geodesy. The principal scientific disciplines comprise entire hierarchies of special sciences. Thus, for instance, physics is divided into mechanics, heat,

optics, electricity, atomic physics, etc. In its turn, mechanics can be divided into the mechanics of solids, hydromechanics, and aeromechanics. The mechanics of solids is further subdivided into statics, kinematics, and dynamics.

A characteristic feature of mathematics (or the mathematical sciences) is that it encroaches to a considerable degree upon other scientific disciplines, particularly the natural and engineering sciences. It seems that a similar position will in the future be taken up by cybernetics, which cannot very well be included in any of the classes mentioned above. This is because cybernetics treats problems concerning forms of organization in any objects, no matter what branch of science they belong to.

Individual sciences will frequently be found to overlap to some extent. This is how interdisciplinary sciences, which actually belong simultaneously to two fundamental scientific disciplines, come into being. Among the best known let us quote, for instance, mathematical physics, physical chemistry, biophysics and biochemistry. As will be seen in the next section, the emergence of cybernetics has also given rise to a whole series of new interdisciplinary sciences.

3.7 Special Branches in Cybernetics

Although cybernetics is still a very young science, certain tendencies to subdivide it are already appearing, particularly for two reasons:

1. Natural endeavours aiming at an efficient division of labour in cybernetics, called forth by the ever-growing number of new discoveries;

2. Overlapping with other scientific disciplines.

It is too soon yet to speak of a real "division of labour"; some typical trends are, however, already beginning to appear in the work of cyberneticists. It seems that in future the following three main branches will be the first to become permanently established in cybernetics:

1. *Theoretical cybernetics*, in which so far three fundamental aspects manifest themselves most strongly:

a) *the theory of systems transmitting information*,

b) *the theory of systems which process information,*

c) *the theory of control.*

2. *Experimental cybernetics,* directed chiefly towards cybernetic modelling as an aid to epistemology.

3. *Engineering cybernetics,* which treats the problems concerned with the design and construction of engineering cybernetic systems. For this field, cybernetic modelling is also of considerable importance, since many engineering cybernetic systems are produced as models of other systems, e.g. biological, psychological, mathematical and other ones.

Where cybernetics overlaps with other scientific disciplines, new interdisciplinary sciences arise.

Of great importance is the overlapping of cybernetics and mathematics, especially in the sense that cybernetics abundantly utilizes already existing mathematical theories and instigates the foundation of new trends in mathematics. This fact sometimes leads to the impression that cybernetics is a mathematical discipline. This conclusion is incorrect, of course, since cybernetics utilizes, besides the apparatus of mathematics, other resources as well.

Cybernetics also overlaps to an important degree with biology. We shall later devote great attention to the resulting interdisciplinary science. The field simultaneously covered by cybernetics and biology is frequently termed *neurocybernetics* [B 7]. We do not believe this name to be sufficiently expressive of the field covered, since cybernetic phenomena in living organisms need not always be of nervous origin. In our opinion, the name *biocybernetics* would far better serve our purpose, being analogous with the well-established terms biochemistry and biophysics. *Neurocybernetics* would then stand for one of the special branches of biocybernetics.

At the present, cybernetics is found to have many features in common with psychology, psychiatry and, possibly, pedagogy. According to present developments, very close relations may be expected to be set up in the near future between these fields on the one hand and cybernetics on the other, and a new independent interdisciplinary science will evidently emerge, the subject of which will be the study of psychological systems from the point of view of cybernetics. This new branch might very well be covered by the name *psychocybernetics.*

In many ways, cybernetics also encroaches upon the engineering sciences, especially by presenting a general theory for the design of the most diverse devices. The relation between cybernetics and engineering chiefly concerns the fields of data processing machines, automatic regulation, and communication engineering. The term *engineering cybernetics* [A30] has already become established for the interdisciplinary science between engineering in a wider sense and cybernetics. It seems likely that engineering cybernetics will have to be subdivided into narrower fields.

Engineering cybernetics is sometimes confused with bionics. In such cases we are concerned with an obvious mistake. *Bionics* [B42] is an interdisciplinary science between biology and engineering; its subject is the application of biological principles to engineering. The principles involved, e. g. the transformation of chemical into mechanical energy, photosynthesis, etc., need not concern cybernetics in all aspects. On the other hand, engineering cybernetics deals frequently with systems that are not inspired by biology.

An interesting relation is becoming established between cybernetics and linguistics. This relation leads to the emergence not only of a number of theoretical problems connected especially with information theory in its wider sense (the problem of the amount of information in language, the understanding of texts, etc.), but also of many practical problems (machine translation, abstracts, information language, etc). Here we are concerned with very difficult problems, the majority of which have so far been only partially solved. The contents of this discipline, which is still being formed, would be very well expressed by the name *cybernetic linguistics.*

Cybernetics and one of the youngest scientific disciplines, *semiotics*, can also be observed to have many problems in common. This branch of science deals with arbitrary systems of signs used in human society.

Cybernetics is of considerable importance to economics and also to sociology. In this instance we are chiefly concerned with problems of the control of the national economy and with the control of society in a wider sense. Here the terms *cybernetic economy* and *cybernetic sociology* would be satisfactory.

Cybernetics also encroaches upon the most diverse branches of medicine [A22]. Here we are primarily concerned with new diagnostic

methods, the design of artificial organs and limbs, problems of bio-electro-stimulation, etc. This field also includes problems concerning the pathology of mechanisms controlling the metabolism of cells (see Chapter 9). It seems that, in this connection, cybernetics can contribute considerably to the detailed exploration of the causes of one of the most fearsome diseases of our time – cancer – and that it is also capable of contributing to the discovery of effective preventive and curative methods for the suppression of this disease. The name *medical cybernetics* has come into use for the combination of cybernetics with medicine.

For the time being, a lesser influence is exerted by cybernetics upon chemistry, physics, jurisprudence, history, and fine arts.

CHAPTER 4

CYBERNETIC SYSTEMS

In Chapter 2 we treated systems from a broader aspect. We shall now proceed to mark out only those of the previously considered systems which are of interest to cybernetics. These are the systems to which we shall later devote our main attention.

4.1 Changes in Systems

Every system is defined (see Sec. 2.5) on the one hand by its universe $\mathbf{A}$, i.e. by the set of its elements, on the other hand by its characteristic $\mathbf{R}$, i.e. by the set of relationships both between the elements of set $\mathbf{A}$, and between these elements and the environment of the system.

Now let us consider a system $\mathbf{S}_1 = \{\mathbf{A}_1, \mathbf{R}_1\}$, defined in some object from a certain point of view. From this system we can pass to another system $\mathbf{S}_2 = \{\mathbf{A}_2, \mathbf{R}_2\}$, defined in the same object from the same point of view, by one of the three following procedures:

1) change of universe,

2) change of characteristic,

3) change of both universe and characteristic.

Two types of changes must be distinguished, both in the universe and in the characteristic.

Changes of the first type concern only an increase or reduction in resolution level. These manifest themselves in the universe in that some elements of system $\mathbf{S}_1$ are divided into several partial elements or, conversely, in that some elements of system $\mathbf{S}_1$ are combined to form a single element. In the characteristic, a change of the first type manifests itself

by an increase or reduction in the number of variables in the relationships $\boldsymbol{r}_{ij}$.

It is easy to ascertain that changes of the first type lead to different systems within the framework of the same super-system (see Sec. 2.12).

The second type of change reveals itself in the universe by the introduction into the system $\mathbf{S}_2$ of new elements which were not contained in system $\mathbf{S}_1$ (i. e. which were not part of its elements) or, conversely, by the elimination of some of the elements of system $\mathbf{S}_1$. In the characteristic this type of change shows by an exchange of some relationships $\boldsymbol{r}_{ij} = 0$ for relationships $\boldsymbol{r}_{ij} \neq 0$, or vice versa.

Any change of the second type necessarily leads always to a change of the super-system. Since we assumed, however, that the viewpoint remains the same, we shall only be concerned with changes within a certain class of super-systems.

4.2 THE CYBERNETIC VIEWPOINT

The reader who has carefully read the foregoing explanation is certain to have noticed that a certain object may show different properties depending, on the one hand, on the viewpoint from which it is observed, on the other hand upon changes in the system mentioned in the preceding section.

The viewpoints from which an object is investigated can very roughly be divided into two classes. The first class contains quantitative viewpoints, from which we examine problems concerned with the magnitudes of masses and energies, their mutual effects and evolution in the system itself as well as between the system and its environment, etc. Such viewpoints find their widest field of application in the natural sciences. They will be called *mass-energy viewpoints*.

The second class comprises viewpoints from which problems are examined which are concerned with organization in its widest sense, its evolution within the system, transfer between elements of the system and between the system and its environment, etc. Since organization is the carrier of information, and it is the information aspect which chiefly interests us in organization, we are concerned in this class of viewpoints

essentially with information problems. This class will be called *cybernetic viewpoints.*

Even though cybernetic viewpoints find their application in all the sciences, cybernetics emerged as a separate branch of science treating the information properties of various organizations without regard to their physical carrier. The title of cybernetics to the rank of an independ-

SCIENCE	Physics	Biology	Economics	Linguistics	Cybernetics
VIEWPOINT 1. Mass-energy 2. Cybernetic	1 2	1 2	1 2	2	2
SUBJECT OF INVESTIGATION	inanimate matter	animate matter	political economy	language	organization
EXAMPLES	1. $F = m.a$, and similar relations between physical quantities 2. evolution of entropy in a concrete physical system	1. metabolism, conditions of existence of organism 2. transfer of genetic information, excitability, self-organization	1. relations between sellers and buyers 2. control of economy, economic decision-making	2. information content of language, syntax, translations	2. classification of organization, study of individual classes of organizations

Fig. 4.1. Illustration of the two basic viewpoints used in the investigation of systems

ent science follows from the extent and complexity of the problems involved and from the great importance of their solution to other sciences.

Quantitative problems of a mass-energy character cannot be entirely separated from problems of organization. When investigating metabolism, for instance (see Chapter 9), we will be concerned – according to our classification – with the examination of a living organism from a viewpoint of the first class. As a matter of course, problems of organization cannot be totally disregarded since the very existence of the living organism depends on a certain organization. It is important, however, that in the given case this organization is only presumed, but neither its static nor its evolutionary properties are subjects of our study. The application of the two classes of viewpoint to some of the sciences is indicated in Fig. 4.1.

Thus, cybernetics is interested only in such relations between the elements of a system which have an information content – considered, how-

ever, from the most varied aspects (see Sec. 3.2). Similarly, cybernetics concerns itself only with such effects of the environment on the system and the system on its environment, which also have an information content. Stimuli, responses, and relations between elements thus have, in physical cybernetic systems, always the character of signals. Inputs, outputs, and couplings between elements then constitute signal paths.

It should be noticed that the cybernetic viewpoint does not limit the universe of the system in any sense. Any universe can thus be part of a cybernetic system. Only its characteristic decides whether a system is cybernetic or not. In this sense we can now clearly state the definition of a cybernetic system:

Definition 4,1. A set $\{\mathbf{A}, \mathbf{R}\}$, where $\mathbf{R}$ is the set of informational or signal relationships $\mathbf{r}_{ij}$ $(i, j = 0,1,\ldots, n)$ asserting themselves between the elements of the set $\mathbf{A} = \{a_1, a_2,\ldots, a_n\}$ on the one hand and between these elements and the element a_0 (the environment) on the other hand, is a cybernetic system.

Some authors (e.g. GRENIEWSKI [A16]) use the name "information system" in place of "cybernetic system".

4.3 VARIETY

The concept of *variety* is of great importance in connection with cybernetic systems, since it is associated with organization and thus also with information. Due attention will therefore be devoted to the explanation of this concept.

We relate variety always to some *finite* set of variables if we want to express how many different selections from the values, acquired by these variables, have a meaning under certain conditions. A given selection from the values of variables will be termed the state of the set. From variety we distinguish the so-called *full variety*, which does not change for a given set. Full variety is equal to the number of all possible states of the given set. It is therefore always larger than or at least equal to the actual variety, which will be called simply variety. Denoting a variety of the set $\mathbf{G}$ by the symbol var $(\mathbf{G})$ and the full variety by the symbol

VAR (**G**), we can write

$$\mathrm{var}\,(\mathbf{G}) \leqq \mathrm{VAR}\,(\mathbf{G})\,. \tag{4.1}$$

Full variety depends on the number of variables and on the number of values that can be acquired by these variables. The calculation of the full variety of a given set of variables is thus a purely combinatorial problem.

It is customary to express variety (or full variety) either in absolute units of variety or in bits. *Absolute units of variety*, which we shall denote by the abbreviation *a.u.v.*, express directly the number of possible states of a given set of variables. *Bits*, which we shall denote by the symbol b, express the logarithm to the base 2 of the number mentioned. The method of expressing variety in bits is advantageous chiefly because it shows directly how many elements a set of two-valued variables (elementary quanta of information) would have to possess in order to have the same variety. The conversion of one system of units of variety into the other system of units is performed by means of the relation

$$n[b] = 2^n[\mathrm{a.u.v.}]\,. \tag{4.2}$$

Let us consider the most general case to illustrate the calculation of full variety. Let the set **G** have n variables denoted $g_1, g_2, \ldots, g_n$ respectively and permit the variable g_i to acquire h_i different values (where $i = 1,2,\ldots, n$). The full variety of set **G** can then be calculated from the formulae:

$$\mathrm{VAR}(\mathbf{G}) = \prod_{i=1}^{n} h_i \quad [\mathrm{a.u.v.}]\,, \tag{4.3}$$

$$\mathrm{VAR}(\mathbf{G}) = \log_2 \prod_{i=1}^{n} h_i \quad [b]\,.$$

In the special case, where each of the n variables of set **G** can acquire the same number of values denoted by h, we obtain

$$\mathrm{VAR}(\mathbf{G}) = h^n \quad [\mathrm{a.u.v.}]\,, \tag{4.4}$$

$$\mathrm{VAR}(\mathbf{G}) = n \log_2 h \quad [b]\,.$$

The variety of a distinct set of variables is equal to the full variety of this set only if no restricting conditions apply to the values of their

variables in the given situation, i.e. if there are no relations between the variables. This case occurs very rarely; in the majority of cases, variety is smaller than full variety.

Now let us present a few examples to clarify the concept of variety (and full variety):

Ex. 1. Set **G** consists of three dice which are not interchangeable (e.g., each has a different colour). Since, when casting dice, every die can fall on any of its six faces (the values of the elements of set **G**) whatever the circumstance, we get according to (4.4):

$$var(\mathbf{G}) = VAR(\mathbf{G}) = 6^3 = 216\ [a.u.v.] \doteq 7.75489\ [b]\,.$$

Ex. 2. Set **G** consists of traffic lights at a crossroads: red, amber and green. Each variable of the set **G** can acquire two values: lit and unlit. In accordance with (4.4) we shall easily find that $VAR(\mathbf{G}) = 8\ [a.u.v.] = 3\ [b]$. Let us assume that only one light is permitted to be lit at one time. We thus have $var(\mathbf{G}) = 3\ [a.u.v.] \doteq 1.585$ $[b]$. We see that, to attain this variety, it would have been sufficient to have two lights, the full variety of which is 2 bits ($2 > 1.585$).

Ex. 3. Let us consider some card-game in which cards are put on the table according to certain rules (e.g. rummy, canasta, etc.). Let us assume that the player holds 12 cards (elements of set **G**). Since every card can acquire two positions (in the hand or on the table), the full variety with respect to the cards placed face up on the table is equal to $2^{12}\ [a.u.v.] = 12\ [b]$. Owing to the rules of the game the actual variety is usually smaller and depends upon the mutual relations between the cards according to the rules of the particular game. Let us notice that in this case the variety changes according to how the player exchanges his cards in the course of the game. After any card is put on the table, not only the variety but also the full variety decreases.

Ex. 4. Let us consider three variables. Let the first two be independent and acquire all cardinal values of the decimal digits (the cardinal numbers from 0 to 9); the value of the third variable shall be equal to either

a) the sum of the first two variables, or

b) their product.

Each of the independent variables acquires 10 values. Their variety is thus $10^2 = 100$ $[a.u.v.]$. The variable expressing the sum assumes 19 values, so that the full variety is $19 \times 100 = 1900\ [a.u.v.]$. In the case given above, the variable expressing the product assumes 37 values and the corresponding full variety is thus $37 \times 100 =$ $= 3700\ [a.u.v.]$. The actual variety in both cases is equal to the variety of the independent variables, since the third variable is generated from their values according to a unique prescription. In both cases, the actual variety is thus $100\ [a.u.v.]$. It will be seen that with the product the restriction is stronger than with the sum.

The restriction (constraint) of full variety is of fundamental importance to science. Every scientific law expresses some relation between variables and thus presumes some restriction of full variety. With the aid of scientific laws it is therefore possible to predict (sometimes, of course, only in a statistical sense) the state which a certain set of variables will assume under given conditions. If the elements of the set under consideration were permitted to acquire any arbitrary value under the given conditions, they would be mutually independent and no prediction whatever would be possible. If no reduction of full variety would exist at any time or any place, science would have no meaning whatsoever, quite apart from the fact that there would be no organization and, consequently, no life either.

4.4 VARIETY, ORGANIZATION, AND SYSTEMS

Let us consider a set of variables, each of which changes its value with time. The graph of all quantities of the set under consideration, plotted against time, will be called its *activity*.

Some variety can be found in the activity of any set of variables. If there is full variety, we are concerned with independent variables. In all other cases there exist some *time-invariant relations* between the variables wherein, of course, their past values may assert themselves in addition to their instantaneous values.

If some relations exist between the variables of a given set, we are concerned with an *organized set of variables*. The *organization* of such a set is regarded as the sum of all relations between its elements.

There is a very close connection between the organization of a set of variables and its variety. If, for instance, the variety of the set is full, its organization is zero. By organizing a set of variables, i.e. by introducing relations between the variables, we reduce its variety and vice versa.

Let us illustrate the connection between the variety of a set of variables and its organization by a simple example. Let us again consider the three dice of Ex.1, Sec. 4.3. If the dice are not connected by any relation, the variety of their set is equal to $6^3 = 216$ [*a.u.v.*]. If, however,

we glue the dice together so that they form one piece, the position of any of the dice (the one which at the given moment is regarded as the reference die) uniquely determines the position of the remaining two. In this case, the variety of the set of dice drops to the variety corresponding to a single die, i.e. 6 a.u.v. This reduction of variety occurred because some organization was set up between the dice.

Now let us note that in a system we can define various characteristic sets of variables, in particular:

1) a set $\mathbf{X} = \{x_1, x_2, \ldots, x_p\}$ of variables at the input,
2) a set $\mathbf{Y} = \{y_1, y_2, \ldots, y_q\}$ of variables at the output,
3) a set $\{\mathbf{X}, \mathbf{Y}\}$,
4) a set $\mathbf{Z}_{ij} = \{{}^i w_1, {}^i w_2, \ldots, {}^i w_m, {}^j v_1, {}^j v_2, \ldots, {}^j v_l\}$ of variables at the output of element a_i and at the input of element a_j,
5) a set $\mathbf{V}_i = \{{}^i v_1, {}^i v_2, \ldots, {}^i v_l, {}^i w_1, {}^i w_2, \ldots, {}^i w_m\}$ of variables at the input and output of the same element a_i,
6) a set $\mathbf{C}$ of all different variables in the system.

The variables of the sets under consideration are generated either by the system or by its environment. If any of these sets has some organization, we must assume the system or its environment to possess certain qualities, which permit a set of variables organized in this manner to be generated. The sum of these qualities will be called the *organization of the system*, or the *organization of the environment* (the environment being also a system).

There is no sense in speaking of the organization of a system or its environment unless in connection with a certain distinct set of variables. E.g., the organization of set $\mathbf{X}$ is created by a certain organization of the environment, the organization of set $\mathbf{Y}$ by a certain organization of the system; the organization of set $\mathbf{Z}$ can be created partly by the organization of the environment, partly by that of the system, according to whether we are concerned with input, output, or internal elements.

When assessing the degree of organization in a system, it is sometimes convenient to consider different varieties of the set $\mathbf{Y}$, each of which corresponds to a certain single state of the variables of $\mathbf{X}$. They can be denoted, for instance, by $\mathbf{Y}_{\mathbf{X}}$. It is clear that in combinatorial systems

we have $\mathbf{Y_X} = 1$ for all states of set $\mathbf{X}$. In sequential nets we have $\mathbf{Y_X} > 1$ for at least a single state of set $\mathbf{X}$.

If we experiment with a system regarded as a "black box", we record the activity of set $\{\mathbf{X}, \mathbf{Y}\}$, try to find its organization and, based on this, to set up hypotheses concerning the corresponding organization of the system. Here we know, as a rule, the organization of set $\mathbf{X}$. Of course, we may encounter a case where we do not know at the beginning, which variables belong to set $\mathbf{X}$ and which to set $\mathbf{Y}$.

If we want to find the relationship $\boldsymbol{r}_{ij}$ between two elements a_i and a_j, we must focus our attention on set $\mathbf{Z}_{ij}$. We find the time-invariant relations in the activity of this set of variables and derive from them the relationships between the input quantities of element a_j and the output quantities of element a_i. In the mathematical form of representation we are concerned with finding the equations which satisfy the activity, and explicitly expressing the input quantities of element a_j from these equations.

A convenient methodical approach to the determination of time-invariant relations in a given activity, i.e. to the determination of the organization of a given set of variables, has been suggested by A. Svoboda [B73]. He introduces the concept of a *mask*, with the aid of which he selects samples from the activity. The mask can be selected so that, in a certain position, it uncovers not only the instantaneous values of the variables, but also their past values. So-called *sampling variables* are introduced in this way for a given mask. All relations which remain valid whatever the position of the mask in the direction of the time axis in the activity, i.e. the time-invariant relations between the sampling variables, then belong to the organization.

Let us note that the behaviour of the system as well as that of its environment follow from the organization of set $\{\mathbf{X}, \mathbf{Y}\}$. From this point of view A. Svoboda suggests [B74] a fundamental approach to the classification of digital systems (see Sec. 4.7). It must by remembered, however, that the classification of a certain system is not absolute but depends on the choice of the observation mask.

The problems hinted at in this section are fundamental for the construction of a cybernetic theory of systems, since it is just the various forms of organization as carriers of information that are the subject of

interest to cybernetics. Little, however, has been done as yet in this respect. But A. Svoboda's papers referred to above are a good foundation upon which to build a theory of cybernetic systems.

4.5 Time Relations

In Chapter 2 we defined the behaviour of a system as the dependence of the reactions of the system on the stimuli of the environment, regardless of whether the response of the system follows immediately upon the arrival of the stimulus, or whether there is a time delay between stimulus and response.

Both cases are possible theoretically (in abstract systems). In physical systems, however, the response is always dalayed with respect to the stimulus. This delay is called the reaction time of the system.

The reaction time of a system depends, on the one hand, on the reaction time of the elements which generate the response of the system corresponding to the given stimulus, on the other hand on the method of

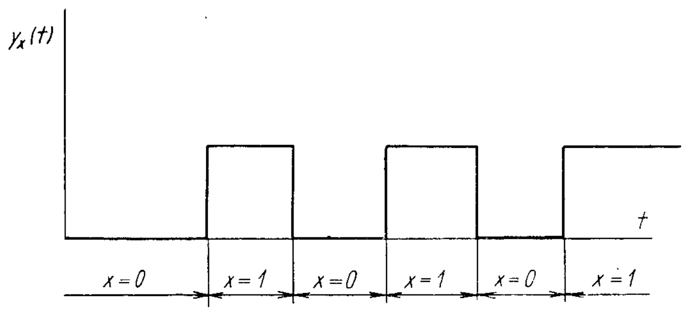

Fig. 4.2. Example of constant reaction time function of a combinatorial system with zero reaction time

coupling between these elements. In a combinatorial system, the reaction time thus depends on the kind of stimulus, in a sequential system on the sequence of the stimuli, and in a random system it can be derived neither from the stimuli, nor from their sequence. With series couplings of several elements their reaction times sum up. The reaction time of a phys-

ical system is, however, sometimes so short that it can be disregarded for practical purposes.

The response of a system to a given stimulus, which asserts itself in the output of the system after the reaction time has passed, is in general a function of time. This function will be called the reaction time function.

To a given stimulus $\mathbf{x}$ we thus allocate by means of the transformation $\boldsymbol{T}$ (see Sec. 2.7) a *reaction time function*, generally denoted by $\mathbf{y}_x(t)$.

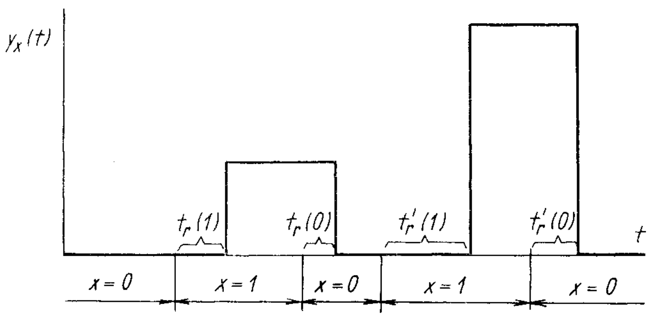

Fig. 4.3. Example of constant reaction time function of a sequential or random system

Let us illustrate this by a very simple system possessing only one input x and one output y. Let us assume that the input can acquire only two values (1 bit of information), denoted by 0 and 1 respectively, whereas no restriction applies to the output values. The reaction time of this system to the stimulus 0 is denoted by $t_r(0)$, the reaction time to the stimulus 1 by $t_r(1)$.

Figs. 4.2 to 4.4 show examples of reaction time functions for the system under investigation. Fig. 4.2 illustrates the simplest possible type of system, i.e. a combinatorial system with a contant reaction time function and zero reaction time. Fig. 4.3 shows a sequential system (different reactions to the same stimulus) with a constant reaction time function and with reaction times depending upon the sequence of stimuli. Fig. 4.4 represents the example of a general time function. In continuous engineering systems we speak in this connection of the response of the given system to a unit pulse applied to its input.

In Figs. 4.2 to 4.4 we were able to show graphic examples of some reaction time functions, only because we considered a system with a single output. Only in this case the vector $\mathbf{y}_{\mathbf{x}}(t)$ has the properties of a scalar, whose values can be plotted in a plane system of Cartesian co-ordinates in dependence upon the time and the stimulus. However, we must remember that, with several outputs present, it would be impossible to illustrate in a plane the reaction time functions in the manner described.

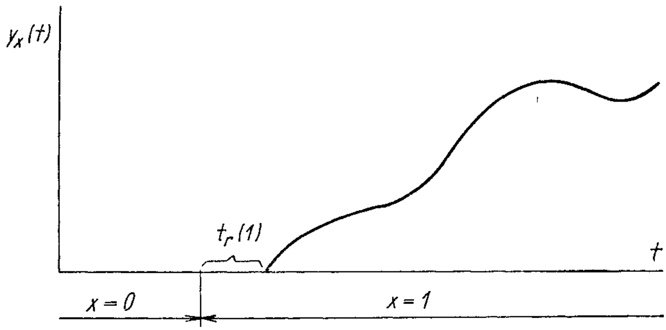

Fig. 4.4. Example of a general reaction time function

4.6 Stability

When assessing a system from the point of view of behaviour, three kinds of state can generally be distinguished in it:

1. *Equilibrial state* – for a constant $\mathbf{x}$, $\mathbf{y}$ is also constant.

2. *Oscillatory equilibrial state* – for a constant $\mathbf{x}$, $\mathbf{y}_{\mathbf{x}}(t)$ is a periodic function.

3. *Non-equilibrial state* – for a constant $\mathbf{x}$, $\mathbf{y}_{\mathbf{x}}(t)$ is a non-periodic function.

The non-equilibrial state may be either permanent or occurs only for a limited period of time. In such a case we speak of a transient state or a transient process. The transient process is characterized by the fact that, for a constant $\mathbf{x}$, either the relation

$$\lim_{t \to \infty} \Delta \mathbf{y}_{\mathbf{x}}(t) = 0 \tag{4.5}$$

is satisfied, where

$$\Delta \mathbf{y}_x(t) = \mathbf{y}_x(t) - \mathbf{K} \tag{4.6}$$

and where the symbol $\mathbf{K}$ denotes a constant vector for the given system and given stimulus (or sequence of stimuli), or $\mathbf{y}_x(t)$ is a periodic function for $t \to \infty$.

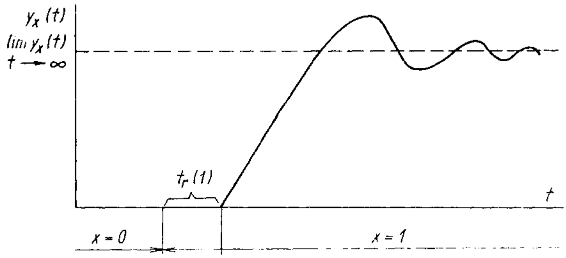

Fig. 4.5. Example of the reaction time function of a stable system

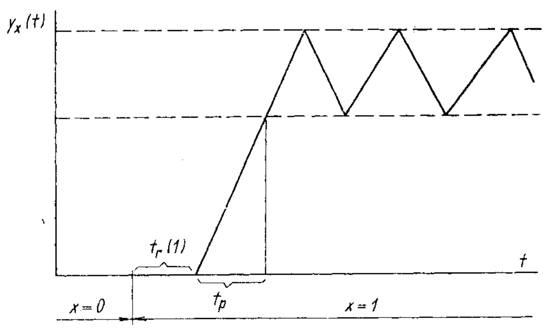

Fig. 4.6. Example of the reaction time function of an oscillatory system

If the relation (4.5) is satisfied for all stimuli $\mathbf{x}$ which form the input variety of a particular system, the system is said to be stable. When we are concerned with a full input variety, we speak of ultra-stable systems. A system is considered unstable, if the relation (4.5) is not satisfied for at least a single stimulus $\mathbf{x}$ which forms the input variety of the corresponding system. A special place among unstable systems is occupied by oscillatory systems, characterized by the relation (4.5) being satisfied for

some stimuli $\mathbf{x}$ forming the input variety and by $\mathbf{y}_{\mathbf{x}}(t)$ being, for the remaining stimuli, a periodic function for $t \to \infty$.

Fig. 4.5 shows an example of the reaction time function of a stable system possessing a single input and output (see Sec. 4.6). Fig. 4.6 illustrates an example of the reaction time function of an oscillatory system. An example of the general function of an unstable system will be found in Fig. 4.4.

4.7 Types of Systems

The classification of general systems, which also relates to cybernetic systems, has been dealt with from various aspects in Sec. 2.12 on the one hand, and elsewhere in the text, as required, on the other hand. Here we discuss a special classification, which has no meaning except for cybernetic systems.

According to the kind of quantities observed in the system, cybernetic systems can be divided into *analogue* and *digital* (discrete) ones.

With analogue systems, an analogue code (see Sec. 3.4) is used to represent the information. The vectors $\mathbf{x}$ and $\mathbf{y}$ vary continuously and the relationships $\mathbf{r}_{ij}$ are continuous vector functions. In this case, there is no sense in speaking of a variety of the set of variables since the variables acquire all values within a particular interval, i.e. an infinite number of values. There is, however, sense in speaking of the organization of the set of variables, since different relations may exist between the variables. The general mathematical medium suitable for expressing these relations is a system of differential equations.

In digital (discrete) systems, information is represented by a digital code. Here we always consider only a finite number of stable states of the vectors $\mathbf{x}$ and $\mathbf{y}$. It is true that continuous changes of the aforesaid vectors can occur between these states. However, these are transient changes which do not in principle interest us. In digital systems, the functions $\mathbf{r}_{ij}$ are discontinuous (e.g. logical functions, etc.). A suitable medium for expressing relations between variables in digital systems of a certain kind is Boolean algebra, in which sampling variables occur in the sense of the paper [B 73] already referred to. The equations corre-

spond to the differential equations used in analogue systems, the temporal depth of the mask corresponding to the order of differentiation.

The properties of analogue signals very sharply limit the kind of information they are capable of representing. This may be only information having the value of some continuous variable. Moreover, as we shall see later, every analogue system can always be approximated to any desired degree of accuracy by a suitable digital system.

In addition to analogue and digital systems there also exist so-called *hybrid systems*, which operate with both analogue and digital signals.

In conjunction with the representation of information by signals and vice versa in a given system, it is important to note the difference between the representation at the input and that at the output. The allocation of the signal to the information is essential in the representation at the input, the representation is therefore required to be unique in the direction from the information to the corresponding signal. Conversely, at the output, the representation is required to be unique in the direction from the signal to the corresponding information which is being represented.

From the standpoint of behaviour, cybernetic systems may be classified according to the manner in which the input information or signals are transformed into the output. As an example, let us list some of these classes:

1) *Communication systems.* Their function consists merely in transmitting signals in space. The fundamental demand made on communication systems is that the information contained in the signals does not get lost in the course of transmission. Further requirements are added in engineering systems, such as economy of solution, speed of signal transmission (reaction time of the system), etc.

2) *Memory (storage) systems.* Their function consists in storing the information received. As in communication systems, the basic requirement is that the information stored does not get lost. In engineering systems moreover we are interested chiefly in the reaction time of the system and usually also in the economy of solution and in the dimensions per unit of information.

3) *Decoders (code transformers).* These are combinatorial systems possessing the same variety at the input as at the output. Representation

of input and output signals is mutually unique, i.e. the appropriate output signal can be uniquely derived from the given input signal and vice versa.

4) *Function generators*. These are combinatorial systems, the variety of which at the output is smaller than or at most equal to the variety at the input. An output signal is uniquely assigned to each input signal; the converse, however, does not apply. In general, it is thus not possible to derive from the output signal the corresponding input signal. H. GRENIEWSKI [A 16] calls these systems prospective.

5) *Retrospective systems*. These are sequential or random systems, the output variety of which is larger than the input variety and in which the corresponding input signal can be uniquely derived from any output signal.

6) *Self-organizing systems*. These are sequential or random systems in which the number of responses to a given stimulus may change (decrease, as a rule) under certain circumstances (the variety $\mathbf{Y}_{\mathbf{X}}$ in the sense of Sec. 4.4).

The classification of cybernetic systems from the viewpoint of structure is very complicated. We shall therefore leave this question open for the time being and revert to it later several times in connection with some concrete types of systems.

CHAPTER 5

MODELLING

If we compare different systems in nature, we often find pairs of systems which resemble each other from a certain point of view. In such cases we may sometimes consider one of these systems as the model of the other system and duly utilize it in this function. Whether a particular system may be considered as the model of another system depends, of course, to a considerable degree on the sense in which we want the model to substitute for the original system, i.e. to what purpose we want to use the model.

Similarities exist not only between pairs of physical systems, but also between abstract systems and sometimes between an abstract system on the one hand and a physical system on the other.

The aforementioned similarities between different systems have been utilized intuitively by man since ancient times, in science as well as in the fine arts. At the present, however, science is getting more and more interested in this field, both in a theoretical sense (improving the accuracy of definition of the model concept, determining the limits of the usability of models, etc.), and in the practical application of models (for instance in psychology, economics, linguistics, the engineering sciences, etc.). It seems that this all-pervading increase in the interest in modelling problems has been contributed to chiefly by cybernetics since, in cybernetics, organizational forms are studied independently of their carrier so that, in a certain sense, cybernetic systems constitute common models of systems defined in different, frequently widely remote, scientific disciplines.

There is a tendency to utilize these common models as much as possible, both epistemologically and practically.

The aim of this chapter is to analyse the concept of the similarity of two systems, to give a general definition of the model concept and to

define the viewpoint from which cybernetics assesses the similarity of systems. This chapter also contains an outline of the classification of cybernetic models and gives a survey of the field in which cybernetic models are most frequently used.

5.1 THE SIMILARITY OF SYSTEMS

If we want to assess the similarity ot two systems, we must first make clear from what standpoint we are interested in similarity in the given case. There may be many aspects from which to judge the similarity between systems. For instance, there are similarities in form (morphological), similarities in complexity, similarity of the universe or characteristic, similarities in behaviour, etc. However, not every similarity need be considered as a model. The meaning ascribed to the model concept is thus narrower than that of the similarity concept. Moreover, we endeavour to define the model concept as accurately as possible, whereas with the similarity concept we often content ourselves with an intuitive explanation.

Modelling is thus understood to be a definite, clearly delimited kind of similarity between systems. In cybernetics we are usually interested, from the standpoint of modelling, in two kinds of similarity:

1. Similarity in the behaviour of two systems; we then speak of a *model of behaviour.*

2. Similarities in the universe together with similarities in the characteristic of two systems; we then speak of a *model of the system* which, of course, is simultaneously a model of behaviour.

At this point let us remark, that it is the model of behaviour which is particularly typical of cybernetics, and we may rightly say that this approach to modelling is one of the chief contributions of cybernetics to the general methodology of science. This is why greater attention is devoted in this book to models of behaviour than to those of systems.

Now let us note that the conception of a system in the general sense (see Chapter 2) is closely linked with the idea of similarity. In support of this statement let us imagine some different types of system, e.g. bio-

logical, physical, mathematical, psychological, cybernetic, and economic. Each of these systems is characterized in a different way, both as far as contents and terminology are concerned:

1. *The biological system.* This is defined for living objects. When describing its behaviour, the observer (experimenter) relies on the concepts of excitation (stimulus) and response (reaction). The part of the

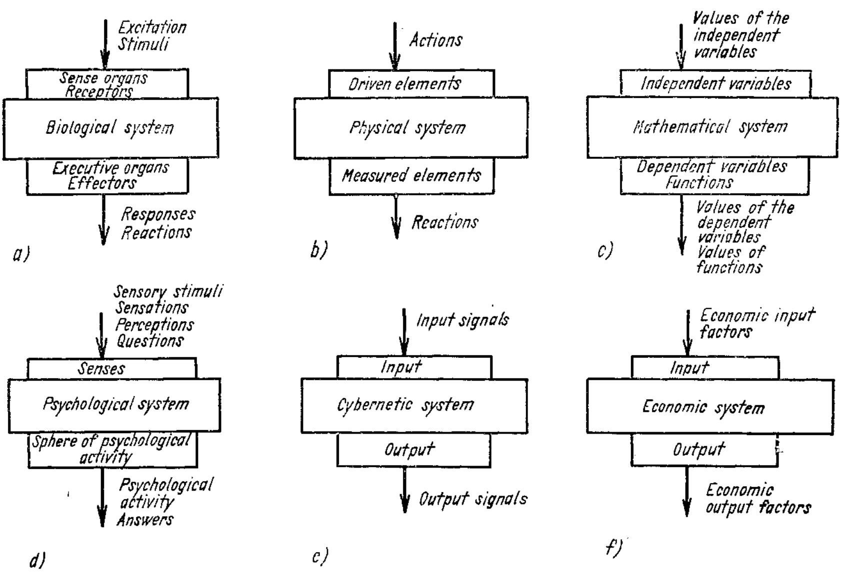

Fig. 5.1. Similarities between various types of system and differences in terminology

system that is sensitive to excitation is called the receptor, the part which performs the reaction is called executive organ or effector (Fig. 5.1a).

2. *The physical system.* This is defined for any physical object. In descriptions of its behaviour we encounter the concepts of action and reaction. The action is started by the experimenter, for instance, by his exciting certain elements (excited or driven elements), i.e. he alters the values of the appropriate (input) physical quantities. He then measures the corresponding reaction on other elements (Fig. 5.1b).

3. *The mathematical system.* If we confine ourselves, for the sake of simplicity, to a system of equations, we may say that different values of the independent variables enter the system through these variables. Conversely, different values of the dependent variables leave the system with their aid (Fig. 5.1c).

4. *The psychological system.* For simplicity let us imagine, in our case, a system to which various questions are put. The system accepts these questions by means of receptors and answers them with the help of effectors (Fig. 5.1d).

5. *The cybernetic system.* This system receives input signals through its input. The information contained in the input signals is processed within the system, and at the output there appear output signals which are the result of this process (Fig. 5.1e).

6. *The economic system.* This system receives economic input factors through its input, and at its output there appear economic output factors (Fig. 5.1f).

It will be noted that from the point of view of the external observer, there exist certain similarities between the systems briefly described, that are clearly evident from Fig. 5.1. Thus, for instance, excitation in the biological system corresponds to action, the values of independent variables, question, input signal, economic input factors, etc., in the other systems. The same similarities would be found from the point of view of an internal observer (an observer of structure). These similarities entitle us to speak of different systems in a common language. We thus arrive at the concept of a general system, conceived in the manner already treated in Chapter 2.

When choosing concepts for the description of the general system, we usually employ some appropriate equivalent concept, namely that which is the most satisfactory from the semantic point of view in the given context. We therefore sometimes speak of a system of equations as of a system which we excite by different values of the independent variables and whose response we then observe. On the other hand, at other times we speak of a biological system as though its receptor were entered by the value of some independent variable, for which the system determines the corresponding values of the dependent variable on the basis

of a process occurring within. However, the general theory of systems endeavours to introduce uniformity into the terminology used to describe systems. For the time being, this endeavour is realized by a preference for some concepts, e.g. input, output, stimulus, response, behaviour, element, coupling, etc.

5.2 THE THEORY OF SIMILARITY

Now let us demonstrate, based on the classical theory of similarity, in what manner the concept of "similarity" can be defined with greater accuracy and what conditions must be fulfilled by the model to satisfy this theory. As we shall later see, we are concerned here solely with one of the special approaches to modelling. The cybernetic approach to modelling is substantially more general. The problems involved in this approach are, however, far more complicated, and have not yet been elaborated in a unified manner.

The classical theory of similarity treats the properties of mutually similar physical systems. Hereby we mean systems described by the same mathematical equations, but with the corresponding constants and variables in the two systems representing, in general, different physical quantities. If the mutually corresponding pairs of quantities are simply increased or reduced at a certain ratio, we are concerned with a special case.

Let us assume that the space-time relations between the quantities $x_1, x_2, \ldots, x_n$, which interest us in the physical system $\mathbf{S}_1$, are expressed by the equations

$$\begin{aligned} f_1(x_1, x_2, \ldots, x_n, t) &= 0\,, \\ f_2(x_1, x_2, \ldots, x_n, t) &= 0\,, \\ \ldots\ldots\ldots&\ldots\ldots \\ f_m(x_1, x_2, \ldots, x_n, t) &= 0\,, \end{aligned} \tag{5.1}$$

where t denotes time.

Let us further assume that the space-time relations between the quanti-

ties $X_1, X_2, \ldots, X_n$ of the physical system $\mathbf{S}_2$ are expressed by the equations,

$$
\begin{aligned}
&F_1(X_1, X_2, \ldots, X_n, t) = 0\,, \\
&F_2(X_1, X_2, \ldots, X_n, t) = 0\,, \\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
&F_m(X_1, X_2, \ldots, X_n, t) = 0\,,
\end{aligned} \tag{5.2}
$$

where the expression F_1 is isomorphic to the expression f_1, expression F_2 is isomorphic to f_2, etc. The isomorphic relation, explained and defined in Sec. 5.11, is used here in the following sense: The constants and variables in the expressions listed above represent elements, and the mathematical operations (addition, multiplication, division, differentiation, integration, etc.) form relations between these elements.

Suppose that we want to substitute system $\mathbf{S}_1$ by system $\mathbf{S}_2$ in such a manner as to obtain, when experimenting with system $\mathbf{S}_2$, the same results as though we were experimenting with system $\mathbf{S}_1$. If such a transformation is possible, system $\mathbf{S}_2$ will be considered as the physical model of system $\mathbf{S}_1$ in the sense of the classical theory of similarity, from the point of view of the variables $x_1, x_2, \ldots, x_n$.

It is known that the isomorphic relation between the expressions f_i and F_i (where $i = 1,2,\ldots, m$) is a necessary condition for the system $\mathbf{S}_2$ to be usable as a physical model in the sense considered, but it is not a sufficient condition. The fundamental requirements are that the ratio between the mutually corresponding quantities in the original and in the model be constant, i.e.

$$
\begin{aligned}
&\frac{x_1}{X_1} = C_1\,, \\
&\frac{x_2}{X_2} = C_2\,, \\
&\ldots\ldots\ldots \\
&\frac{x_n}{X_n} = C_n\,.
\end{aligned} \tag{5.3}
$$

Let us call the constants $C_1, C_2, \ldots, C_n$ *constants of similarity*.

Now let us substitute $X_1, X_2, \ldots, X_n$ in Eqs. (5.2) by the corresponding expressions from Eqs. (5,3). We obtain the equations

$$
\begin{aligned}
&F_1(x_1, x_2, \ldots, x_n, t, C_1, C_2, \ldots, C_n) = 0\,,\\
&F_2(x_1, x_2, \ldots, x_n, t, C_1, C_2, \ldots, C_n) = 0\,,\\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\
&F_m(x_1, x_2, \ldots, x_n, t, C_1, C_2, \ldots, C_n) = 0\,.
\end{aligned}
\tag{5.4}
$$

In a physical model of the type under consideration we want Eqs. (5.4) to be identical with Eqs. (5.1). If this condition is to be fulfilled, then it is necessary that certain relations between the constants of similarity be satisfied. Let us denote them, for instance, as follows:

$$
\begin{aligned}
&g_1(C_1, C_2, \ldots, C_n) = 0\,,\\
&g_2(C_1, C_2, \ldots, C_n) = 0\,,\\
&\ldots\ldots\ldots\ldots\ldots\ldots
\end{aligned}
\tag{5.5}
$$

These relations, which we shall call *indicators of similarity*, are obtained by equating Eqs.(5.4) with Eqs.(5.1).

The indicators of similarity (5.5) are, as a rule, such that several constants of similarity may be chosen at will and the remaining ones determined according to the relations (5.5). In this way a certain freedom in the choice of the model is preserved, so that it is possible to choose the most advantagenous model from the given point of view.

If the constants of similarity in (5.5) are substituted by the expressions (5.3), we obtain the relations

$$
\begin{aligned}
&h_1(x_1, x_2, \ldots, x_n) = h_1(X_1, X_2, \ldots, X_n)\,,\\
&h_2(x_1, x_2, \ldots, x_n) = h_2(X_1, X_2, \ldots, X_n)\,,\\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\,,
\end{aligned}
\tag{5.6}
$$

where the expressions $h_1, h_2, \ldots,$ represent quantities having the same values in the original and in the model. These are usually called *invariants* (or *criteria*) *of similarity*.

It is possible to show that the invariants of similarity are dimension-

less quantities. However, we are not going to deal with the classical theory of similarity in such detail. The reader interested in this aspect is therefore referred to some literary sources listed in the bibliography [B 23, B 36, B 41a].

5.3 THE ABSTRACT MODEL

The behaviour of systems has already been treated in Chapter 2. Now let us dwell on what we consider as the *known behaviour* of a system and what we consider to be the *explanation of this behaviour*.

Let us start from the assumption that we consider as known only such behaviour that is uniquely described (with random behaviour we have only a statistical description). We may also say that we know the behaviour of a system insomuch as we know its description.

The knowledge of behaviour thus depends on the knowledge of its description. Things are similar as far as the explanation of behaviour is concerned. When explaining what process within the system leads to a certain behaviour, we again rely on a description of the corresponding process. The behaviour is considered as being explained to the same degree to which we know the description of this process. However, we know from the foregoing explanation that the behaviour of a system can be uniquely described on the basis of the knowledge of its structure.

The experimenter produces the description of the behaviour or structure of a system on the basis of the observation of the corresponding system. First he writes down a protocol on the observed relations. He then looks for connections in the protocol and tries to express them by words, pictures, mathematical symbols, etc.

If we compared the description of behaviour or structure with the corresponding actual behaviour or structure, we would find (possibly to our own surprise) that the concept of description is understood to mean the creation of the same relationships as the relationships observed, except that these new relationships are produced by a different system. This may be, for instance, a mathematical system, a propositional system, a system of ideas, etc. We shall call this new system *the abstract model of behaviour or of structure.*

5.4 The Model of Behaviour

Now let us enunciate a theorem, which at first sight might seem self-evident and let it be known for further use as theorem 5.1:

If two systems exhibit equal behaviour, one of them may be used as a model of the behaviour of the other one.

As far as systems of the same kind are concerned, this theorem is certain to be understood by everybody and to be doubtlessly accepted as valid by every reader. In this case, the term "equal" must be understood in the sense of Leibniz' criterion [C 38], which says: "$x = y$ if, and only if, x has every property which y has, and y has every property which x has". Theorem 5.1 then follows from the theory of similarity,

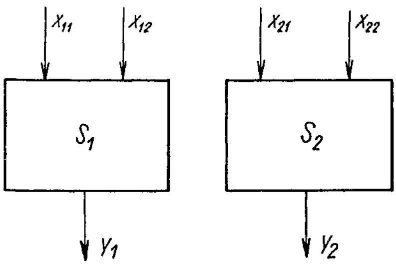

Fig. 5.2. Pair of systems illustrating the example in Sec. 5.5

dealt with in Sec. 5.2. In this book, however, theorem 5.1 interests us in a far wider sense. It interests us mainly in those cases, where we are concerned with two systems each of which belongs to a different branch of science. We mean, for instance, systems belonging to the inanimate world, by the aid of which we want to model animate systems. In order to be able to acknowledge the validity of the theorem even in such cases we must first, however, devote our attention to two concepts: *equal behaviour*, and *model*. In analysing them we shall see that the validity of theorem 5.1 is closely bound up with our idea of these two concepts. We may speak of the general validity of the theorem only on the basis of an accurate definition of the two concepts mentioned. The next few sections are devoted to this purpose.

5.5 EXAMPLES OF EQUAL BEHAVIOUR

Let us consider two systems one of which, $\mathbf{S}_1$, is the *modelled* and the other, $\mathbf{S}_2$, the *modelling* system. Let us assume that each of the two systems has two elementary inputs and one elementary output. The inputs and outputs of the two systems will be denoted according to Fig. 5.2. Let us further assume that each elementary input may acquire only two values, denoted by 0 and 1 respectively. Supposing that the input and output varieties of both systems are equal to the full variety, then the following stimuli and responses (where x_{11}, x_{12}, x_{21}, x_{22} are partial stimuli and y_1, y_2 are responses) will be possible:

System $\mathbf{S}_1$: x_{11} x_{12} ,

x_{11}	x_{12}
0	0
0	1
1	0
1	1

system $\mathbf{S}_2$: x_{21} x_{22} ,

x_{21}	x_{22}
0	0
0	1
1	0
1	1

System $\mathbf{S}_1$: y_1 ,

y_1
0
1

system $\mathbf{S}_2$: y_2 ,

y_2
0
1

Let us choose some kind of behaviour of system $\mathbf{S}_1$ by selecting a particular relationship between stimuli and responses. For instance, let the relationship be specified by the following table:

x_{11}	x_{12}	y_1
0	0	0
0	1	1
1	0	0
1	1	0

If we wanted to describe the behaviour defined by this table verbally, we would say that system $\mathbf{S}_1$ produces the response 1 only for the stimulus $x_{11} = 0$ and $x_{12} = 1$. In all other cases it produces the response 0.

Now let us assume that system $\mathbf{S}_2$ will behave according to the following table:

x_{21}	x_{22}	y_2
0	0	0
0	1	1
1	0	0
1	1	0

A look at this table will show us that system $\mathbf{S}_2$ has the same behaviour as system $\mathbf{S}_1$, since it also gives the response 1 only for the stimulus $x_{21} = 0$ and $x_{22} = 1$. Here, however, we must point out a very important circumstance which we have so far passed over in silence. That is, we assumed that the elementary input x_{21} of system $\mathbf{S}_2$ is assigned to the elementary input x_{11} of system $\mathbf{S}_1$, and that the elementary input x_{22} of system $\mathbf{S}_2$ is assigned to the elementary input x_{12} of system $\mathbf{S}_1$.

Now let us assume that system $\mathbf{S}_2$ behaves according to a different table:

x_{21}	x_{22}	y_2
0	0	0
0	1	0
1	0	1
1	1	0

Is the behaviour of this system the same as that of system $\mathbf{S}_1$? The attentive reader is certain to have noticed that the answer to this question is closely connected with the manner in which we assigned the elementary inputs of the two systems to each other. At first sight it is evident that, when using the preceding assignment, the behaviour of system $\mathbf{S}_2$ would differ from that of system $\mathbf{S}_1$. If, however, we assign the input x_{11} to input x_{22}, and the input x_{12} to input x_{21}, systems $\mathbf{S}_1$ and $\mathbf{S}_2$ will again show the same behaviour and one of them may serve, in accordance with theorem 5.1, as the model of the other from the point of view of behaviour.

We must, however, stop at yet another example. Let us assume that the system $\mathbf{S}_2$ behaves, this time, according to the table

x_{21}	x_{22}	y_2
0	0	1
0	1	0
1	0	0
1	1	0

If we want the system $\mathbf{S}_2$ to have, in this case, the same behaviour as system $\mathbf{S}_1$, it is not enough to assign the individual elementary input elements of the two systems in a suitable manner. We may, however, attain our goal by introducing into the suitable assignments such transformations which ascribe to the values of the stimuli of one system the values of the corresponding stimuli of the other system. In our case, assignment as well as transformation are very simple: to the input x_{11} we assign the input x_{21}, to the input x_{12} the input x_{22}, and we introduce a transformation which ascribes the partial stimulus $x_{22} = 1$ to the partial stimulus $x_{12} = 0$ and, conversely, the partial stimulus $x_{22} = 0$ to the partial stimulus $x_{12} = 1$.

5.6 INPUT AND OUTPUT MAPPING

A suitable assignment of partial inputs of one system to those of another combined with the corresponding transformational relations between the stimuli will be called *input mapping*. Similar assignments and transformations also interest us in the outputs of the two systems – we then speak of *output mapping*.

With regard to established practice, we shall use the concept of mapping in such a manner that, when the input is concerned, we shall always speak of a *mapping of the stimuli of the modelled system in the stimuli of the modelling system*, whereas on the output side we shall always speak of a *mapping of the responses of the modelling system in the responses of the modelled system*.

All the facts presented so far in connection with the modelling of behaviour are schematically illustrated in Fig. 5.3.

So as not to have to rely always on a verbal expression of the manner in which the mapping is to be performed, it is frequently written out in

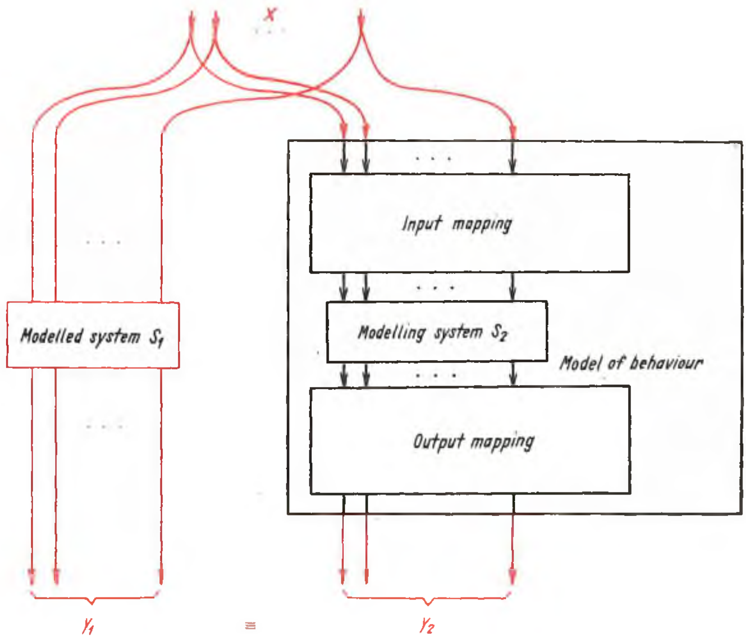

Fig. 5.3. Schematic illustration of the relations between modelled and modelling system

the form of equations. These are then called input and output *mapping equations*. The determination of suitable mapping equations is sometimes very difficult.

The peculiar circumstance that in models of behaviour it is not only the behaviour of the modelling system proper that is of importance, but also the input and output mapping, is frequently utilized for modelling the behaviour of different systems by means of a single piece of equipment. As a simple illustration of this statement, let us consider the slide rule. This is a device consisting of two parts, one of which slides in the other. When each of the parts is fitted with logarithmic scales, the slide

rule can be used for multiplication. If we used linear scales, we might utilize the same device for addition. The replacement of logarithmic scales by linear scales and vice versa is nothing else than a change in the input and output mapping. In the first case the slide rule models a mathematical system whose behaviour is defined by the product of two numbers, in the second case the same slide rule models a different mathematical system, whose behaviour is defined by the sum of two numbers.

In the example described above, the modelling of various systems by the same slide rule was made possible by choosing different mapping equations for each instance. In general, however, it is not always possible to use mapping equations for modelling. This is because we do not model mathematical systems only. Particularly difficult cases are encountered especially when we are concerned with systems of the living world on the one hand and inanimate systems on the other. Therefore, we shall henceforth prefer the more general concept of *mapping*, no matter whether equations or other means will be used for its determination.

5.7 The Definition of Equal Behaviour

On the basis of the preceding exposition we can now more accurately state the concept of equal behaviour, on which the theorem 5.1 is founded. With regard to the importance of this concept, a separate definition will be used to make clear its exact meaning.

Definition 5.1: *Two systems have the same behaviour, if equal stimuli always evoke the same responses in both systems, equal stimuli (or equal responses) of two systems being pairs of stimuli (or responses) mutually assigned to each other by a definite input and output mapping.*

As far as this definition is concerned, however, it should be noted that a time component may, if necessary, be included in the concept of equal stimuli (or equal responses). This time component (determining, for instance, what sequence of stimuli in one system corresponds to the sequence in the other system) then also forms part of the mapping. It should also be noted that time in one system need not necessarily be represented as time in the other system, since this kind of mapping is not tied to the physical nature of the stimulus or response and is thus also independent of the physical dimension.

5.8 THE DEFINITION OF THE MODEL OF BEHAVIOUR

We have already used the model concept intuitively in theorem 5.1. However, only now can we proceed to define it accurately.

Let us assume that $\mathbf{S}_1$ is a system whose behaviour we want to model. Let us further assume that $\mathbf{S}_2$ is the system by means of which the behaviour of system $\mathbf{S}_1$ is to be modelled. Not only the system $\mathbf{S}_2$, but also the corresponding input and output mapping will then belong to the model of the behaviour of system $\mathbf{S}_1$.

When speaking in the foregoing section of equal behaviour, we used mapping as a means for comparing the stimuli or responses of the two systems. However, when speaking of the model of behaviour, we think of the input and output mapping as part of it (Fig. 5.3).

Let us also note that in the model we do not require a reciprocally unique mapping. It is fully sufficient to have a unidirectionally unique mapping, i.e. a mapping where a single resulting value corresponds to each value to be represented, but not vice versa (see Sec. 5.6).

It now only remains to enunciate the definition of the model of behaviour which, on the whole, follows from the foregoing exposition. This definition, together with the definition of equal behaviour (definition 5.1), provides the basis of theorem 5.1.

Definition 5.2: *Every system* $\mathbf{S}_2$ *with its input and output mapping, in which all stimuli of system* $\mathbf{S}_1$ *are transformed – after performing the input and output mapping – in such a manner that they evoke the same responses as in system* $\mathbf{S}_1$, *is a model of the behaviour of system* $\mathbf{S}_1$.

5.9 THE STRUCTURE OF BEHAVIOUR

When reading the preceding sections, some of the following questions must have occurred to many readers: Is it always possible to find an input and output mapping such that a particular system $\mathbf{S}_2$ can be used to model the behaviour of the given system $\mathbf{S}_1$? Under what conditions is it possible to find a mapping such that a certain system $\mathbf{S}_2$ can be used for modelling the behaviour of the given system $\mathbf{S}_1$, and when is this impossible?

These questions are very important to the theory of modelling. In this section we shall therefore at least try to answer them in outline.

In mathematical systems we speak in connection with similar questions of *topological properties*. If we are to prove that there exist certain transformations of some system, it is sufficient to prove that this system has the appropriate topological properties.

In computers, the concept of *internal functional structure* in used in connection with problems of mapping. This concept is employed to denote just that property which decides whether a certain system can be used as a model of behaviour of another system. With regard to our general approach to the problems of modelling it will be suitable to call the afore-mentioned property the *structure of behaviour*. This is invariant with respect to the input and output mapping, and may be defined as follows:

The behaviour of system $\mathbf{S}_2$ *has the same structure as that of system* $\mathbf{S}_1$, *if there exists an input and an output mapping such that with it the system* $\mathbf{S}_2$ *is a model of the behaviour of system* $\mathbf{S}_1$.

On the basis of this definition we may meditate as follows: If we express the structures of behaviour of two systems in a suitable manner, a comparison of these structures will show whether there exists (in the case of equal structures of behaviour) or does not exist (in the case of different structures of behaviour) a mapping such that with its aid it will be possible to attain the same behaviour in both systems. If we find the structures of behaviour of the two systems to be equal, we must yet determine a suitable mapping – a task that is often rather difficult.

Thus, if we want to find a system by means of which we would be able to model our system $\mathbf{S}_1$, we must solve two partial problems:

1. *Find a system* $\mathbf{S}_2$ *that has the same structure of behaviour as* system $\mathbf{S}_1$.
2. *Determine the appropriate input and output mapping for system* $\mathbf{S}_2$.

Let us note that systems can be compared according to their structure of behaviour, namely by including in the same class, relating to a certain system $\mathbf{S}$, all systems having the same structure of behaviour as the corresponding system $\mathbf{S}$.

We shall return to the problem of equal structure at the end of this chapter, in Sec. 5.18, which has been added for the benefit of those readers who want to penetrate more deeply into the problems of the model of behaviour.

5.10 THE MODEL OF A SYSTEM

In Sec. 5.1 we already mentioned that models of behaviour must be distinguished from models of systems. The fundamental properties of the models of behaviour have been outlined in the preceding sections. We shall now proceed to the models of systems.

Right at the outset it should be realized that every model of a system is at the same time a model of the behaviour of this system, but that a model of behaviour need not always be a model of the system. The set of models of some system **S** thus contains always less than or, at the most, the same number of elements as the set of models of behaviour of this system.

The principle of modelling one system by means of another is based on the concepts of the *isomorphy* and *homomorphy* of two systems. These concepts must therefore be exactly defined. Let us, however, first illustrate their meaning by means of a few examples.

For instance, a map and the countryside it represents can be isomorphic from the geometrical point of view. What we have in mind is the fact that to each element on the map (e.g. point, curve, conventional symbol, etc.) there corresponds uniquely a certain element in the countryside, the geometrical relationships between the elements on the map being the same as those between the corresponding elements in the countryside. There is, however, no sense in speaking of isomorphism in this case unless we assume that the countryside is being assessed at a certain resolution level (see Sec. 2.3) for which the converse assignment is also valid, i.e. that to each element in the countryside we uniquely assign a certain element in the map, and that to each geometrical relationship between elements in the countryside we uniquely assign a relationship between the corresponding elements on the map.

If we assessed the countryside at a higher resolution level, we could distinguish a greater number of elements and relations in it than on the

map. In such a case we would no longer be concerned with an isomorphic, but with a homomorphic relation, which applies in one direction only.

A typical isomorphy of physical systems will be seen to exist, for instance, between mechanical and electrical systems. That is to say, for every mechanical system there exists an isomorphic electrical system and vice versa. In this case we speak of an analogy between mechanical and electrical systems. Assignments in this analogy are not unique. For instance, we can choose the following pairs: force – voltage, speed – current, mass – inductance, elasticity – capacitance, mechanical resistance – electrical resistance, deflection – charge, etc., the relations between the listed quantities of the electrical and mechanical systems respectively being expressed by equations showing the same form. This analogy is usually utilized in such a manner that complicated mechanical or acoustic systems are modelled by electrical systems, which are easier to realize and the computational methods for which are better known. The electrical models (actual or only abstract) are then used to ascertain various properties within them, and these are then projected back into the original mechanical or acoustic system. The theory of similarity, already mentioned in Sec. 5.2, is fully utilized in this field. In a similar manner, electrical systems can be used to model thermal, hydraulic and other systems.

An example of an abstract model is provided by every differential equation that expresses relations between the quantities of a given physical system.

The few examples given above may have sufficiently illustrated the importance of isomorphy. As will be seen later, isomorphy is also of great importance to the theory of deductive systems and in many other theoretical fields.

5.11 Isomorphic Systems

In the preceding section we introduced the concepts of isomorphy and homomorphy and illustrated them by a few examples. We shall now proceed to give an exact definition of these concepts, which are of supreme importance to the theory of modelling.

In the remaining part of this chapter we shall mostly speak of the relations between two systems. Let us denote these systems (in agreement with Sec. 2.5) by $\mathbf{S}_1 = \{\mathbf{A}_1, \mathbf{R}_1\}$ and $\mathbf{S}_2 = \{\mathbf{A}_2, \mathbf{R}_2\}$ respectively. We shall use this notation consistently in the following definitions.

Definition 5.4. *The systems* $\mathbf{S}_1$ *and* $\mathbf{S}_2$ *are isomorphic if and only if:*

1. *the elements of universe* $\mathbf{A}_1$ *can be mutually uniquely assigned to the elements of universe* $\mathbf{A}_2$, *i.e. if it is possible to assign to every element of universe* $\mathbf{A}_1$ *uniquely an element of universe* $\mathbf{A}_2$ *and vice versa,*

2. *the elements of characteristic* $\mathbf{R}_1$ *can be mutually uniquely assigned to the elements of characteristic* $\mathbf{R}_2$ *in such a manner, that to each element of the characteristics* $\mathbf{R}_1$ *which expresses an oriented relation between two elements of universe* $\mathbf{A}_1$ *we always assign that element of the characteristic* $\mathbf{R}_2$ *that expresses the same oriented relation between the corresponding pair of elements of the universe* $\mathbf{A}_2$ *in the sense of Para. 1 of this definition.*

Let us note that an important result follows from Para.1 of Definition 5.4: Two finite isomorphic systems must necessarily have the same number of elements. A similar result also follows from Para.2 of Definition 5.4: two finite isomorphic systems must of necessity have an equal number of non-zero elements in the characteristic.

An isomorphic relation between two systems $\mathbf{S}_1$ and $\mathbf{S}_2$ will be denoted symbolically by $(\mathbf{S}_1\, i\, \mathbf{S}_2)$, where the symbol i is intended to remind us of the term "isomorphic". It is evident from Definition 5.4 that

$$(\mathbf{S}_1\, i\, \mathbf{S}_2) = (\mathbf{S}_2\, i\, \mathbf{S}_1)\,, \tag{5.7}$$

i.e. the isomorphic relation is symmetrical. It is also reflexive, i.e. the relation $(\mathbf{S}\, i\, \mathbf{S})$ is always satisfied for any system $\mathbf{S}$.

Isomorphy also possesses the transitive property, i.e. $(\mathbf{S}_1\, i\, \mathbf{S}_3)$, provided that $(\mathbf{S}_1\, i\, \mathbf{S}_2)$ and $(\mathbf{S}_2\, i\, \mathbf{S}_3)$ are valid at the same time.

Now let us note that Definition 5.4 does not state expressly whether we are concerned with physical or abstract systems. This is because isomorphy exists not only in pairs of physical systems, but also in pairs of abstract systems and in pairs consisting of one physical and one abstract system.

5.12 Homomorphic Systems

Let us again consider two systems $\mathbf{S}_1 = \{\mathbf{A}_1, \mathbf{R}_1\}$ and $\mathbf{S}_2 = \{\mathbf{A}_1, \mathbf{R}_2\}$, and define their homomorphic relation.

Definition 5.5: *Systems $\mathbf{S}_1$ nad $\mathbf{S}_2$ are homomorphic if and only if:*

1. *elements of universe $\mathbf{A}_2$ can be uniquely assigned to the elements of universe $\mathbf{A}_1$, i.e. if it is possible to assign to every element of universe $\mathbf{A}_1$ uniquely an element of universe $\mathbf{A}_2$, while the converse assignment, i.e. the assignment of elements of universe $\mathbf{A}_1$ to the elements of universe $\mathbf{A}_2$ is not unique;*

2. *the elements of characteristic $\mathbf{R}_2$ can be uniquely assigned to the elements of characteristic $\mathbf{R}_1$ in such a manner, that to each element of characteristic $\mathbf{R}_1$, which expresses an oriented relationship between two elements of universe $\mathbf{A}_1$, we always assign that element of characteristic $\mathbf{R}_2$ which expresses an equally oriented relation between the corresponding pair of elements in the universe $\mathbf{A}_2$ in the sense of Para. 1 of this definition. At the same time it is assumed that the assignment of the elements of characteristic $\mathbf{R}_1$ to those of characteristic $\mathbf{R}_2$ is not unique.*

From Definition 5.5 it follows clearly that, as distinct from isomorphy, the homomorphy of two systems is a unidirectional relation. This is because homomorphy requires system $\mathbf{S}_1$ to possess a greater number of elements than system $\mathbf{S}_2$.

Let us denote the homomorphic relation of two systems $\mathbf{S}_1$ and $\mathbf{S}_2$ by the symbolic notation $(\mathbf{S}_1\, h\, \mathbf{S}_2)$, read "system $\mathbf{S}_2$ is homomorphic with system $\mathbf{S}_1$". From Definition 5.5 it is obvious that

$$(\mathbf{S}_1\, h\, \mathbf{S}_2) \neq (\mathbf{S}_2\, h\, \mathbf{S}_1)\,, \tag{5.8}$$

i.e. the homomorphic relation is not symmetrical; homomorphy, however, possesses the reflexive and transitive properties.

Let us assume that system $\mathbf{S}_1$ has n elements and system $\mathbf{S}_2$ m elements. Let us further assume that system $\mathbf{S}_2$ is homomorphic with system $\mathbf{S}_1$, i.e. $(\mathbf{S}_1\, h\, \mathbf{S}_2)$. Then n must necessarily be greater than m, and system $\mathbf{S}_1$ possesses m groups of elements to which always the same element of system $\mathbf{S}_2$ is assigned. If we consider only a single element of every group of this kind in relation to system $\mathbf{S}_2$, we speak of the *kernel of homo-*

morphy. If the numbers of elements in the individual groups are denoted by the symbols $n_1, n_2, \ldots, n_m$, where

$$\sum_{i=1}^{m} n_i = n,$$

it is easy to ascertain that for the number P_j of all different kernels of homomorphy we have

$$P_j = \prod_{i=1}^{m} n_i \,. \tag{5.9}$$

Every kernel of homomorphy is characterized by the fact that, within its framework, the relation of the two systems is isomorphic. Homomorphy is therefore sometimes called many-valued isomorphy.

To illustrate the kernel of homomorphy, Fig. 5.4 presents an example of the homomorphic assignment of the elements of universe $\mathbf{A}_2$ to those

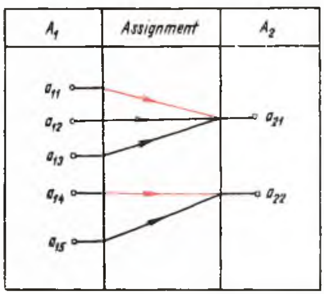

Fig. 5.4. Example of homomorphic assignment between the elements of two universes

of universe $\mathbf{A}_1$. Universe $\mathbf{A}_1$ has five elements ($n = 5$), universe $\mathbf{A}_2$ has two ($m = 2$). Universe $\mathbf{A}_1$ therefore comprises two groups of elements, one of which contains three elements (a_{11}, a_{12}, a_{13}), the other two elements (a_{14}, a_{15}). Thus, $n_1 = 3$, $n_2 = 2$, and according to (5.9) there exist therefore six ($n_1 \,.\, n_2 = 6$) different kernels of homomorphy. One of the possible kernels in Fig. 5.4 is marked red.

5.13 Definition of the Model of a System

Based on the concepts of isomorphy and homomorphy, we can now very easily define the model of a system.

Definition 5.6: System $\mathbf{S}_2 = \{\mathbf{A}_2, \mathbf{R}_2\}$ is a model of the system $\mathbf{S}_1 = \{\mathbf{A}_1, \mathbf{R}_1\}$ if the two systems are isomorphic and the mapping of $\mathbf{R}_1$ in $\mathbf{R}_2$ is such that, with the same stimulus of the environment acting on both systems, the mutually corresponding elements of $\mathbf{A}_1$ and $\mathbf{A}_2$ show the same responses.

Should we more closely investigate, under what assumptions there exists a mapping of $\mathbf{R}_1$ in $\mathbf{R}_2$ such as required by Definition 5.6, we would find that the structure of behaviour of the mutually assigned elements in the two systems must be the same (see Sec. 5.18).

It will be useful to introduce yet another definition of the model of a system based on homomorphy, i.e. which assumes that the systems $\mathbf{S}_1$ and $\mathbf{S}_2$ as defined by 5.6 are only homomorphic. In this connection we shall speak of a *homomorphic model.*

As will be seen in the following section, the relation between a model and a homomorphic model of a system is associated mainly with the resolution level (see Sec. 2.3).

The modelled system (system $\mathbf{S}_1$ in the sense of Definition 5.6) will sometimes be called the *original.*

5.14 MODELS AND THE RESOLUTION LEVEL

Fig. 5.5 shows an example of resolution graphs (see Sec. 2.4) for three different super-systems (see Sec. 2.12) denoted by $\mathbf{N}_1$, $\mathbf{N}_2$ and $\mathbf{N}_3$ respectively. Let us remember that every node of the resolution graph represents one system.

In Fig. 5.5 the individual systems are marked by numbers. Where an isomorphic relation exists between two systems, the corresponding nodes are marked by the same number and, for clarity, they are connected by red lines. In these cases one system may constitute the model of the other system and vice versa. We must distinguish two cases here:

1. Both isomorphic systems belong to the same super-system.

2. Each of the pair of isomorphic systems belongs to a different super-system.

In the first case, a necessary (but by no means sufficient) condition is that both systems be of the same order in the sense of the classification presented in Sec. 2.12. This applies to node 4 in super-system $\mathbf{N}_1$ and node 21 in super-system $\mathbf{N}_2$.

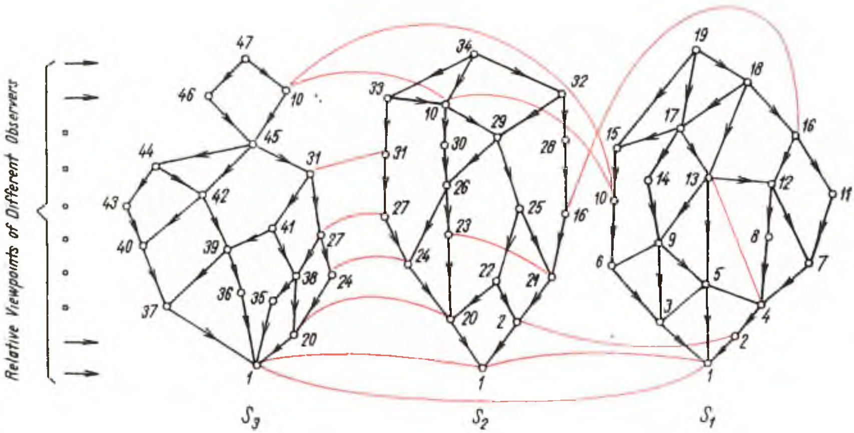

Fig. 5.5. Example of the possibilities of modelling within the framework of three super-systems

In the second case we may be concerned with systems of different order, provided that we would assign zero order to the starting (i.e. the lowest) node in all the super-systems under consideration. E.g., the system corresponding to node 10 is of the third order in super-system $\mathbf{N}_1$, of the fifth order in super-system $\mathbf{N}_2$, and of the sixth order in super-system $\mathbf{N}_3$.

It will be seen from Fig. 5.5 that, from the viewpoint of modelling, the relations between two or several super-systems can widely differ from each other. Let us note, for instance, the pair of super-systems $\mathbf{N}_1$ and $\mathbf{N}_2$. It is true that the conditions of isomorphy are satisfied at the lowest resolution level (nodes 1), but modelling has no meaning at this level. If we pass with both super-systems in certain directions to a higher resolution level (nodes 2), then modelling remains applicable. However, if we pass to a higher resolution level over other paths (e.g. into nodes 3, 5, or 20), the isomorphic relation is disturbed and it is therefore no

longer possible to speak of modelling. If, however, we pass on to a still higher level in a suitable manner, the isomorphic relation may reappear (nodes 10 and 16).

It is interesting to note that a given super-system (e.g. $\mathbf{N}_2$) may, at some resolution levels, constitute the model of another super-system (e.g. at the levels 1, 2, 10 and 16 it is a model of super-system $\mathbf{N}_1$), whereas at other resolution levels it is the model of some other super-system (e.g. at the levels 1, 20, 24, 27 and 31 it is a model of super-system $\mathbf{N}_3$). It sometimes happens that a super-system is, at a particular resolution level, a model of several super-systems, also considered at certain (but mutually different) resolution levels, e.g. node 10.

When we want to remain with the original at a certain resolution level, even though there is no possibility of modelling the original at this level, we must content ourselves in case of necessity with a homomorphic model. E.g., the system corresponding to node 2 in the super-system $\mathbf{N}_1$ or $\mathbf{N}_2$ is a homomorphic model of the system that corresponds to node 4.

5.15 EXAMPLES OF MODELS

We frequently encounter the principle of modelling without being aware of it. E.g., if we want to explain something to another person, we use expressive pictures, i.e. geometrical models. We also use a similar method when we want to explain the shape of a mathematical function or relations between physical quantities. Photos, sculptures, paintings and films are also models of real systems. We may speak even of literary works (e.g. historical ones) as of models of social, economic, ethical and other relations. In the same manner we may speak of linguistic models in the case of translations, of topographical models in the case of maps, etc.

Modelling in science and engineering is, of course, of far greater importance than in everyday life. Some branches, e.g. that of computing machines, descriptive geometry, engineering drawing, comparative physiology and others are based directly on modelling. Models are used in other fields whenever they are more advantageous and more accessible to study than the originals. As a rule, this is the case when the direct

investigation of the original is impossible, dangerous, costly, difficult, tedious, inexpedient, etc.

The use of models in science is as old as science itself. Thus, for instance, the primitive scientific ideas on the universe in antiquity may already be considered as its abstract model. This model has undergone continuous improvement on the basis of the ever-growing body of knowledge. Newton's model was far more accurate, Einstein's model is still more accurate, etc.

An important example of a model is every interpretation of a formal system, created axiomatically (deductively). The axioms define a set of elements and the properties of certain operations on these elements, from which there also follow the formal properties of the elements proper. The model is created by assigning a concrete meaning to the individual (formally introduced) elements. In this case the model may be an abstract system, but it can just as well be a physical system. Thus, for instance, the propositional calculus, the theory of switching circuits, the theory of classes, etc., are models of a special algebra built up axiomatically. Similarly, Euclidean geometry is one of the possible models satisfying a certain set of axioms.

In this connection we must remember that formal systems are based on formally introduced concepts that have an abstract content only. A vocabulary explaining the concepts of the formal system by means of model concepts is therefore of great importance in the case of models of formal systems. The formally introduced concepts thus acquire a certain meaning. These problems are treated in Ref. [B 34, B 76].

A very important type of modelling in mathematics is represented by various kinds of transformations (e.g. those of Laplace, Fourier, etc.) with the aid of which mathematical systems of one kind, e.g. differential equations, are modelled by other mathematical systems, e.g. algebraic equations. Instead of analyzing the original, we then perform an analysis of the model, which is usually simpler, and apply the results obtained back to the original. In some cases (e.g. for the Laplace transformation) detailed vocabularies have been compiled which determine the input and output mapping for individual elements of the system. These vocabularies help to make modelling very simple.

The sum of all knowledge of a given system, expressed in some kind of language, can also be considered as a model. We then speak of an abstract model. In such a case we may be concerned either with a model of a single system (if the system does not occur repeatedly in nature), or with the model of a whole class of systems which have common properties from the point of view of a given resolution level. As has already been repeatedly emphasized, the main subject of scientific interest is the second case, i.e. the creation of abstract models valid for classes of systems.

Models are very frequently used in engineering. The most easily comprehensible are scale models, which are simply enlarged or reduced in size at a certain scale with respect to the original. They are used, for instance, for investigating the dynamic properties of new designs of aeroplanes, helicopters or rockets in wind tunnels, for testing new types of sea-going ships in special water tanks, for examining the projects of dams, weirs, bridges, and in many other cases. Even though in these cases we are concerned with simple (geometrical) modelling, the results obtained with the model cannot be applied to the original by a simple change of scale. This is because, when reducing (or enlarging) the linear dimensions of the model with respect to the corresponding dimensions of the original at a ratio of, say, $1 : k$, the areas of the model (e.g. the area of the transverse or longitudinal cross-section of an aircraft wing) are reduced (or enlarged) at the ratio of $1 : k^2$ and the volumes at the ratio of $1 : k^3$. The problems associated with the evaluation of results obtained with models of this type are treated by the *theory of similarly*, a subject already touched upon in Sec. 5.2.

Nowadays, far greater importance is being acquired by engineering models which differ from the originals not only in scale, but also by their external shape, physical nature, etc. First among these are computing machines (see Chapters 6 and 7) which model mathematical systems with the aid of physical systems, and simulators, i.e. models which in the given system replace parts that are dangerous, costly or difficult to realize. Medical simulators, such as the artificial heart, artificial kidneys, etc., deserve special attention. It may be expected that in the future the principles of modelling will lead to remarkable results particularly in this field.

Let us present yet another simple example to emphasize the difference between models of behaviour and models of structure. The behaviour of the mathematical system

$$y^2 = x_1^2 + x_2^2 \tag{5.10}$$

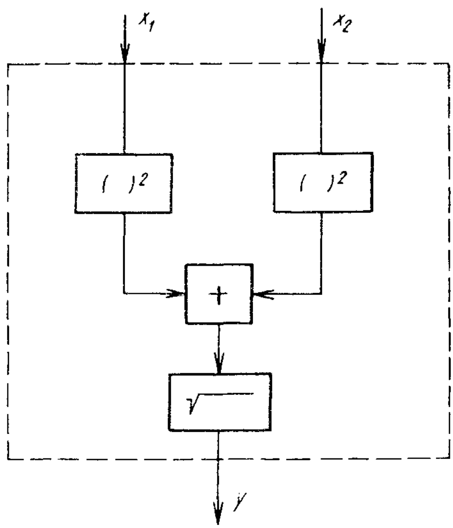

Fig. 5.6. Symbolic model of the mathematical system $y^2 = x_1^2 + x_2^2$

can be modelled by a right-angled triangle, if the sides adjacent to the right angle are considered as the inputs and the hypotenuse as the output. However, in this case we are not concerned with a model of the system (i.e. of the structure), since the isomorphic relation is not satisfied. System (5.10) might be modelled, for instance, by an analogue computer (see Sec. 6.4) according to the symbolic diagram of Fig. 5.6. This would be a model of the system.

We could present many further examples of the use of models in science and engineering. We believe, however, that the few samples given suffice to illustrate the importance and diversity of modelling, the more so since we shall deal concretely with various types of models in subsequent chapters.

5.16 Cybernetic Modelling

Cybernetic modelling is based on the same principle as modelling in any other scientific discipline, i.e. it utilizes the isomorphic (or homomorphic) relation of two systems. Thus, the cybernetic model satisfies, in general, the Definitions 5.4 and 5.6. The peculiarity of cybernetic modelling consists only in the peculiarity of both the system to be modelled (the original) and the model. That is to say, in cybernetic modelling we must assume the original and the model to be systems defined from the cybernetic point of view. The universes of the two systems may be arbitrary, but their characteristics must express the informational relations between the elements of the systems. The cybernetic model can thus be defined in the following manner:

Definition 5.7. *System* $\mathbf{S}_2$ *is called a cybernetic model of system* $\mathbf{S}_1$ *if and only if both systems are cybernetic* (*Definition* 4.1) *and system* $\mathbf{S}_2$ *satisfies Definition* 5.6.

We might define the *homomorphic cybernetic model* in quite an analogous manner.

Of special importance is the case when the universe of the original or model consists of abstract elements, i.e. symbolic blocks without concrete interpretation, where only the inputs and outputs of the blocks are given together with a formal expression of the manner in which the information is processed. For such an abstractly conceived system it is possible to find, in the sense of modelling, many different concrete interpretations distinguished only by the kind of universe and by the types of signal expressing the informational relations which form the characteristic.

We should realize, however, that cybernetics is characterized just by the fact that in very complicated systems, where the study of the complete system meets at the present with unsurmountable difficulties, we direct our attention for the time being to the study of behaviour. At the same time it is indisputable that the study of behaviour alone, even though a makeshift expedient, yields objectively valid and valuable knowledge of systems. A more profound proof of the great epistemological importance of cybernetic models of behaviour, and thus also of the truth of our foregoing assertion, is given by I. B. Novik in Ref. [B49].

Models of behaviour are thus particularly characteristic of cybernetics. In this sense we sometimes speak of a *functional* approach to modelling in cybernetics, or of *iso-functionalism* [A 24, **B** 49].

One of the aids whereby the behaviour of systems can be modelled mathematically, and by means of which it is possible to solve on these models differently formulated requirements concerning the optimal behaviour of systems, is the *mathematical theory of games*. It was founded by one of the greatest mathematicians of the 20th century, JOHN VON NEUMANN (1903 – 1957), an American of Hungarian origin.

5.17 TYPES OF CYBERNETIC MODELS

When speaking of cybernetic modelling, we always assume unconsciously that we are thinking of the modelling of cybernetic systems. Of course, we must always be aware of the fact that cybernetic systems are actually created by our assessing certain objects from the

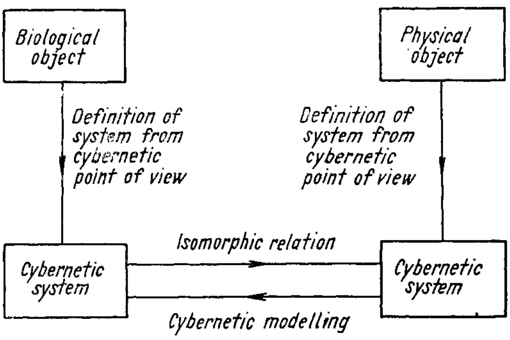

Fig. 5.7. Principles of cybernetic modelling

viewpoint of the information content of the relations between the elements of the system (see Sec. 4.2). By doing this we disregard some traits of these objects while emphasizing others.

For instance, if we want to model some biological object (e.g. a living individual, a nerve cell, the brain, etc.) cybernetically, we must first

apply the cybernetic viewpoint to the object, and based on this define the desired cybernetic system. Only then can we seek another object on which to define the isomorphic system whereby we could model the given cybernetic system. This is schematically illustrated in Fig. 5.7.

Thus, in cybernetic modelling there generally occurs a pair of objects, each of which forms a basis for a definition of the system from the cybernetic point of view. On the basis of such pairs of objects we can suitably classify cybernetic models. In practice, the following pairs come into question: *physical-mathematical*, *mathematical-physical*, *biological-physical*, *biological-mathematical*, *psychological-physical*, *psychological-mathematical*, social-physical, social-mathematical, economic-physical, economic-mathematical, and *linguistic-mathematical*. We shall later direct our attention chiefly to the pairs printed in italics; the remaining cases will be dealt with only briefly.

5.18 Equal Structures of Behaviour

In this section we are going to continue where we left off in Sec. 5.8. The present section is for readers who are more deeply interested in the problems of models of behaviour. It can be left out without detriment to the comprehension of the chapters to follow.

If we want to ascertain whether two systems possess the same structure of behaviour, we must first make clear whether we are concerned with digital or with analogue systems.

In digital systems the structure of behaviour can be expressed very accurately by means of *the behaviour graph*, whose properties have already been described in Sec. 2.15.

The nodes in the behaviour graph correspond to distinct states of the given system. To be more accurate, *every node in the behaviour graph is described by three characteristics:*

1) *stimulus*,
2) *response*,
3) *internal state (state of memory)*.

Let us denote the stimuli by x_i, the responses by y_j and the internal states by z_k (where $i, j, k = 1,2,\ldots$). Any state of the system can then be expressed by the triplet $(\mathbf{x}_i, \mathbf{y}_j, \mathbf{z}_k)$.

A correctly constructed graph of any digital system must meet two fundamental requirements:

1) Two different nodes must differ by at least one characteristic.

2) There must be no two nodes differing from each other only by the characteristic $\mathbf{y}_j$, i.e. by their response only.

When these requirements are satisfied, it is possible to group, with respect to a given reference node $(\mathbf{x}_i, \mathbf{y}_j, \mathbf{z}_k)$, all other nodes of the behaviour graph in one of the following six classes:

$$\left.\begin{array}{rl} \text{I.} & (\mathbf{x}_i, \mathbf{y}_j, \mathbf{z}'_k) \\ \text{II.} & (\mathbf{x}_i, \mathbf{y}'_j, \mathbf{z}'_k) \\ \text{III.} & (\mathbf{x}'_i, \mathbf{y}_j, \mathbf{z}_k) \\ \text{IV.} & (\mathbf{x}'_i, \mathbf{y}_j, \mathbf{z}'_k) \\ \text{V.} & (\mathbf{x}'_i, \mathbf{y}'_j, \mathbf{z}_k) \\ \text{VI.} & (\mathbf{x}'_i, \mathbf{y}'_j, \mathbf{z}'_k) \end{array}\right\} \begin{array}{l} \mathbf{x}'_i \neq \mathbf{x}_i \\ \mathbf{y}'_j \neq \mathbf{y}_j \\ \mathbf{z}'_k \neq \mathbf{z}_k \end{array}$$

Now let us consider some system $\mathbf{S}$. Let us denote its behaviour graph by the symbol $\mathbf{G}$. Let us further assume that $\mathbf{U} = \{u_1, u_2, \ldots, u_n\}$ is the set of nodes in graph $\mathbf{G}$, and that $\mathbf{P} = [p_{ij}]$, where $i, j = 1,2,\ldots, n$, is the transition matrix, whose elements have values defined as follows:

$p_{ij} = 1$, in case that in graph $\mathbf{G}$ there exists an oriented connecting line from node u_i to node u_j,

$p_{ij} = 0$, in case there is no such connecting line.

It is clear that, in the sense of Definition 5.4 (p. 110), we may consider whether two graphs of behaviour, e.g. $\mathbf{G}_1 = \{\mathbf{U}_1, \mathbf{P}_1\}$ and $\mathbf{G}_2 = \{\mathbf{U}_2, \mathbf{P}_2\}$, are isomorphic. This is the case when:

1. the elements of set $\mathbf{U}_1$ can be mutually uniquely assigned to the elements of set $\mathbf{U}_2$,

2. the elements of matrix $\mathbf{P}_1$ can be mutually uniquely assigned to the elements of matrix $\mathbf{P}_2$ in such a manner that every element of matrix $\mathbf{P}_1$ corresponding to a certain pair of elements in set $\mathbf{U}_1$ is of the same value as the element of matrix $\mathbf{P}_2$ which relates to the corresponding pair of elements in set $\mathbf{U}_2$.

In Fig. 5.8 we present, as an example, two isomorphic graphs with their transition matrices. It is easy to ascertain that the elements of sets $\mathbf{U}_1$ and $\mathbf{U}_2$ must be assigned as follows:

$\mathbf{G}_1$		$\mathbf{G}_2$
u_1	$\leftrightarrow$	u_2
u_2	$\leftrightarrow$	u_4
u_3	$\leftrightarrow$	u_1
u_4	$\leftrightarrow$	u_3

Taking the conception of the behaviour graph as a basis, it is clear on the whole that equal structures of behaviour are possessed by two systems such that their behaviour graphs are isomorphic, and where any two mutually assigned nodes always belong, in the sense of this isomorphy and with respect to any other pair of mutually assigned nodes, to the same class according to the classification of nodes presented above.

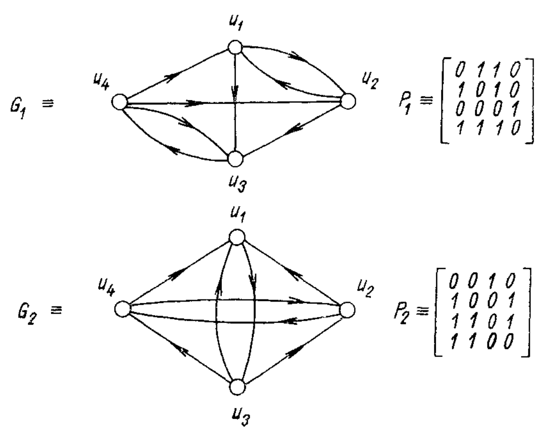

Fig. 5.8. Example of two isomorphic graphs of behaviour

Now let us turn to the problem of analogue systems and explain it by means of an example of the behaviour of two systems $\mathbf{S}_1$ and $\mathbf{S}_2$, each of which has two partial inputs and one output.

Let the behaviour of system $\mathbf{S}_1$ be described by the relation

$$y_1 = F_1(x_{11}, x_{12}) \tag{5.11}$$

and the behaviour of system $\mathbf{S}_2$ by the relation

$$y_2 = F_2(x_{21}, x_{22}),$$

where $x_{11}, x_{12}, x_{21}, x_{22}$ are the corresponding independent variables given within certain intervals, and y_1 and y_2 are the values of the corresponding functions F_1 and F_2.

The further description of the system must be looked upon as follows: If we are concerned with a comparison of the structures of behaviour of the two systems $\mathbf{S}_1$ and $\mathbf{S}_2$, then the following mapping, denoted by f_1, f_2 and f_3, must be mutually unique (one-one). However, if we are concerned with assessing whether system $\mathbf{S}_2$ can be used as a model of the behaviour of system $\mathbf{S}_1$, it will be sufficient for the corresponding mappings to be unique in a single direction, i.e. if they are expressed by functions of the corresponding variables.

Now let us assume that the following mappings exist:

a) Input mapping: $x_{21} = f_1(x_{11}),$

$x_{22} = f_2(x_{12}).$

b) Output mapping: $y_1 = f_3(y_2).$

The behaviour of system $\mathbf{S}_1$, expressed by relation (5.11), can then be rewritten as follows:

$$y_1 = f_3[F_2(x_{21}, x_{22})],$$

and thus

$$y_1 = f_3\{F_2[f_1(x_{11}), f_2(x_{12})]\}. \tag{5.12}$$

Relation (5.12) shows that the value of y_1 can be determined from the values of x_{11} and x_{12} without, however, using the function F_1. After performing the input mappings f_1 and f_2, the calculation is carried out with respect to F_2, whose value is transformed to y_1 by the output mapping f_3.

Thus, if there exist functional mappings f_1, f_2 and f_3 such that the relation (5.12) holds true, we say that function F_2 may be used for modelling the function F_1. In case that f_1, f_2 and f_3 are mutually unique mappings, we may even say that the two functions have equal internal structures.

Example. Let $y_1 = x_{11}x_{12}$ for system $\mathbf{S}_1$,

$y_2 = x_{21} + x_{22}$ for system $\mathbf{S}_2$.

In this case, system $\mathbf{S}_2$ can be used as a model of the behaviour of system $\mathbf{S}_1$, since it is possible to find suitable input and output mappings:

$$x_{21} = \log x_{11}\,,$$

$$x_{22} = \log x_{12}\,,$$

$$y_1 = e^{y_2}\,.$$

In this case, relation (5,12) acquires the form:

$$y_1 = e^{(\log x_{11} + \log x_{12})}\,.$$

The facts presented in this example form, as we know, the basis for the principle of the slide rule, where x_{21}, x_{22} and y_2 are values of lengths on the slide rule, x_{11}, x_{12} and y_1 being the corresponding numerical values of the factors and product respectively.

For those cases where the functions are not given analytically or where an analysis would be too complicated, so-called graphic methods of comparison have been worked out, based on the concept of the *grid structure* [C 37] or *net structure* [B 80] of functions. These methods are used most frequently in the synthesis of analogue function generators.

CHAPTER 6

MODELLING AIDS

In this chapter we shall direct our attention to the description of some of the aids most frequently used at the present for modelling purposes. In this connection we shall devote ourselves mainly to cybernetic modelling.

6.1 A SURVEY OF AIDS TO MODELLING

It is true that, theoretically, there exist an infinite number of devices that can be used to model systems and their behaviour, but only some of them are of practical importance. Among them are various abstract (see Sec. 6.2) as well as engineering aids.

Engineering aids to cybernetic modelling include, on the one hand, various physical systems (particularly electrical networks) designed for single-purpose modelling, and on the other hand data processing machines that can be adapted to model different systems and behaviours.

Data processing machines fall into two basic classes: *analogue computers* and *digital computers.*

Analogue computers (see Sec. 6.4) are capable of modelling only those systems in which the values of stimuli and responses vary continuously. Digital computers, on the contrary, operate with non-continuous (discrete) stimuli and responses. It can be shown, however, that under certain conditions digital computers can be used to model any kind of system.

General-purpose digital computers, which form a special class of digital data processing machines, are the most important modelling aids at the present time. They are characterized by being capable of modelling sys-

tems of arbitrary type, frequently even systems of such extent that cannot be modelled by any other means. They also have the outstanding advantage of permitting changes in models to be performed very easily.

With regard to the great importance of digital computers to modelling, a whole chapter (the seventh) will be devoted to them.

6.2 Abstract Aids to Modelling

In our preceding exposition, an abstract model of the behaviour or structure of a given system was considered to consist of the description of this behaviour or structure. Abstract models are finding use in all problems concerned with systems, particularly in conjunction with the solution of black-box problems.

Abstract models may be expressed by various means, many of which have already been dealt with in our foregoing explanations. The simplest expedient for expressing an abstract model of behaviour is a *verbal description* that states what responses appear at the output of the system as the result of individual stimuli. The insufficient lucidity of this method can be improved upon, for example, by expressing the description in *tabular form*. A still more lucid expedient (especially for expressing sequential behaviour) is the *behaviour graph* already mentioned in Chapter 2.

Let us note that the aforesaid methods describe, properly speaking, the relations between stimuli and steady-state responses, so that they do not take into account the reaction time functions (see Sec. 4.6). Moreover, they cannot be used when stimuli and responses change continuously.

If necessary, every node of the behaviour graph must be supplemented by data on the corresponding reaction time function. It is sometimes enough to quote the time intervals required for the responses to attain steady values, at other times the shape of the reaction time functions must also be known.

Reaction time functions can best be expressed (whenever necessary) by the *algebraic method*, since, as a rule, we are concerned with multidimensional vector functions which cannot be expressed by a plane graph. However, if we are concerned with discrete reaction time functions,

it is sometimes preferable to use the tabular method of expression or to enter the corresponding non-equilibrial states directly into the behaviour graph.

It is difficult to avoid mathematical methods of expression when stimuli and responses change continuously. In these cases the abstract model is represented by systems of algebraic, differential, integral, or integrodifferential equations. This field is dealt with in considerable detail by engineering cybernetics [A 30].

Abstract models of systems (i.e. models of structure) can be expressed, for instance, by *structure matrices* which have been treated in Sec. 2.10. They comprise in detail not only the couplings between the elements of the system, but also the behaviour of these elements.

Another method, which may frequently be expected to be clearer than a matrix, is the representation of the structure of a system by a *symbolic block diagram*. In this instance, every element is usually depicted as a rectangle containing a symbolic representation of the corresponding behaviour, to which are added all passive and active couplings marked in detail. In place of the rectangles, the elements are sometimes represented by conventional schematic symbols the shape of which indicates, according to the convention chosen, the type of behaviour of the elements concerned. This type of symbol includes, for instance, signs for electronic valves, transistors, resistors, capacitors, inductors, contacts, etc. If necessary, these symbols are supplemented by further particulars, e.g. the type of valve or transistor, the value of the resistor, capacitor or inductor, etc.

In the sense quoted, every electrical circuit diagram of some piece of equipment (radio receiver, electronic computer, etc.) is actually an abstract model of the corresponding system. It should be noted that, in this field, the use of symbolic diagrams is far more advantageous than an algebraic description. This has been proved by many years of experience in electrical engineering. At the same time, the structure matrix of a given system and its symbolic diagram may serve as an example of two abstract isomorphic systems, one of which can be used to model the other and vice versa.

Let us mention one more method of abstract modelling, which is of considerable importance to engineering. Although used in various

branches, it is most frequently encountered in electrical engineering. This is the method of *equivalent networks*. The principle of this method of modelling is best explained by the following procedure:

1. An abstract model is constructed, representing the physical system under investigation. This is usually a model expressed by means of a symbolic diagram.

2. Other abstract models are sought, which have different structures but the same behaviour as the original abstract model. This step usually involves finding a structure that contains elements of well-known behaviour. The new model is usually called an equivalent network.

3. The final model (the equivalent network selected) is then used as the basis for the analysis or synthesis of the original system under various special conditions.

Equivalent networks are very frequently used in electrical engineering. As examples let us mention the equivalent networks of electronic valves, transistors, piezoelectric crystals, transformers, power sources, etc.

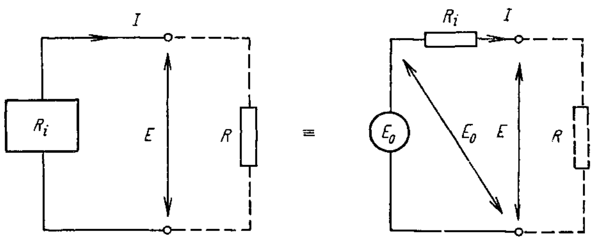

Fig.6.1. Equivalent network of electrical power supply containing an ideal source of voltage

It is sometimes very difficult to prove that the two abstract models (the original and the equivalent network) show the same behaviour. Such proofs form the basis of theorems which are mostly of great practical importance. As an example let us quote Thevenin's theorem which states that any source of electrical energy may be replaced either by an ideal source of voltage having the no-load value of E_0 and with the internal resistance R_i in series (see Fig. 6.1), or by an ideal source of current having the short-circuit value of I_s and with the internal resistance R_i

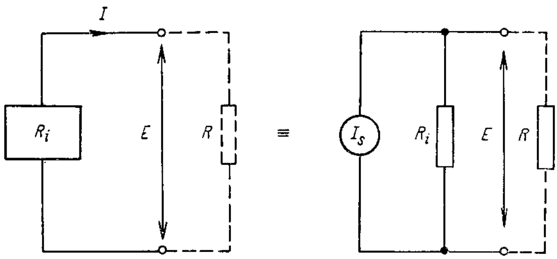

Fig. 6.2. Equivalent network of electrical power supply containing an ideal source of current

in parallel (see Fig. 6.2). An ideal source of voltage is considered to be a source of zero internal resistance, i.e. a source with the constant voltage E_0 across its terminals irrespective of the resistance R of the external load. Conversely, an ideal source of current is a source with infinite internal resistance, with the constant current I_s flowing between its terminals irrespective of the resistance R of the external load.

Thevenin's theorem, which we have just quoted as an example of abstract modelling by equivalent networks, is of extraordinary importance to the theory of electrical systems, since it permits us to base the analysis and synthesis of such systems on pairs of nodes with a constant voltage between them, or branches with constant current flowing through them.

In the theory of electrical networks it is sometimes proved with the aid of equivalent networks that, within the framework of a given type of

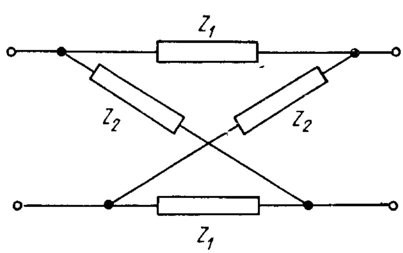

Fig. 6.3. The lattice network — an example of a general abstract model of the behaviour of symmetrical passive four-terminal networks

system, a certain type of structure is the most general one, i.e. that any other type of structure can always be substituted by this most general structure in such a manner, that both systems will show the same behaviour. E.g., in the theory of four-terminal networks it has been proved that the behaviour of any symmetrical passive four-terminal network can always be modelled by a so-called lattice network (see Fig. 6.3).

We shall revert to abstract modelling aids in Chapter 7.

6.3 PHYSICAL MODELS

Physical models utilize the isomorphy between different physical systems. These include, for instance, mechanical, electrical, acoustical, optical, hydraulic, thermal and other systems. The term "physical model" here indicates only that we are concerned with systems defined for objects characterized mainly by properties typical of various branches of physics. Thus, they need not be systems defined from the point of view of physics. If the systems are defined, say, from the cybernetic point of view, their physical nature need not concern us.

In the majority of cases, the physical model is represented by an electrical system, which is the most easy to realize. We sometimes proceed by simply finding for a system which belongs to a certain branch of physics (e.g. heat) an abstract model corresponding to a system taken from another branch (e.g. electricity). On this model we then perform the investigation required and apply the results to the original system. In such a case, however, we are concerned rather with abstract aids to modelling, treated in the preceding section.

As far as actual physical models are concerned, these are mostly used as simulators in various engineering equipment.

6.4 ANALOGUE COMPUTERS

In analogue computers, the situation encountered is substantially contrary to that in abstract aids to modelling. Here we are concerned with physical systems which are used to model mathematical

systems, particularly systems of algebraic and differential equations. We must remember, of course, that the corresponding mathematical systems mostly possess the significance of abstract models of other physical systems. This circumstance, however, is of no importance from the point of view of analogue computers.

We must distinguish, first of all, *special purpose analogue computers* from *general purpose analogue computers.*

Special purpose analogue computers are characterized by being constructed so as to be capable of modelling directly (i.e. without substantially affecting their structure) a certain class of mathematical systems, e.g. linear algebraic equations with a definite number of unknowns. The modelling of a certain concrete mathematical system out of a given class consists, on the one hand, in adjusting the values of the physical quantities that correspond to the coefficients of the pertinent mathematical system (e.g. rotating potentiometers to the proper positions, etc.), and on the other hand in disconnecting, if necessary, some parts of the computer (if, for instance, the number of unknowns is smaller than assumed by the computer).

Special purpose analogue computers are built chiefly for modelling systems of linear algebraic equations *(linear analysers)*, algebraic systems of higher degrees *(polynomial analysers)*, some simple ordinary differential equations (e.g. *harmonic analysers*), partial differential equations, and vector field equations *(electrolytic tanks)*. In addition, simple analogue instruments, such as slide rules, planimeters, integraphs, etc., should also be classed with special purpose analogue computers.

The majority of special purpose analogue computers utilize electrical systems for modelling purposes, with the exception of analogue instruments and some older harmonic analysers which employ mechanical systems.

To illustrate the principles used, we present in Fig. 6.4 the circuit diagram of a simple electrical linear analyser capable of modelling three linear algebraic equations in three unknowns:

$$
\begin{aligned}
A_{11}x + A_{12}y + A_{13}z &= B_1 \,, \\
A_{21}x + A_{22}y + A_{23}z &= B_2 \,, \\
A_{31}x + A_{32}y + A_{33}z &= B_3 \,.
\end{aligned}
\tag{6.1}
$$

Each horizontal lead corresponds to one particular equation and each pair of vertical leads to one unknown. The values of A_{11}, $A_{12}, \ldots, A_{33}$ determine the values of the variable conductances which correspond to the coefficients of the unknowns in the equations of type (6.1) which

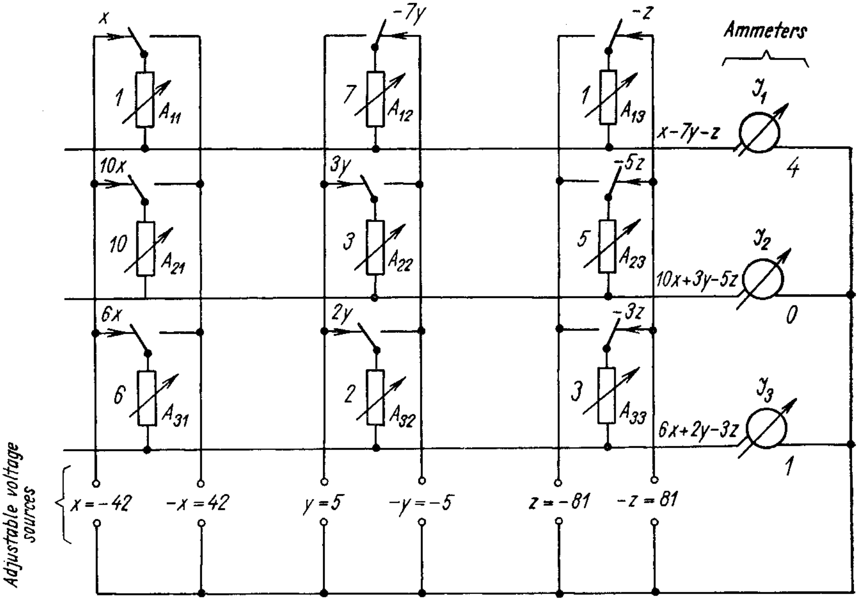

Fig. 6.4. A model for the solution of linear algebraic equations

are to be solved. One terminal of each conductance is connected to one of the horizontal leads, its other terminal to a switch which connects it to either of the two vertical leads. The magnitudes of the conductances and the switch positions are adjusted according to the magnitudes and signs of the corresponding coefficients in the equations to be solved. If a coefficient is positive, the corresponding switch is turned to the left, if it is negative the switch is turned to the right. An ammeter is inserted in each horizontal lead, an adjustable voltage source in each vertical lead. The currents indicated by the ammeters correspond to the quantities B_1, B_2 and B_3 in the equations (6.1). The magnitudes of the voltages

correspond to the values of the unknowns x, y and z. As shown in Fig. 6.4, both positive and negative values of these voltages are available.

Fig. 6.4 illustrates the case when the electrical system models the system of equations

$$\begin{aligned} x - 7y - z &= 4\,, \\ 10x + 3y - 5z &= 0\,, \\ 6x + 2y - 3z &= 1\,. \end{aligned}$$

Far more important for practical purposes and also far more interesting from the point of view of modelling are *general purpose analogue computers*. Their principle consists in that they embody several types of elements the behaviour of which corresponds to some mathematical operations. These operations include, in particular, addition, multiplication by a constant, and integration. These are sometimes supplemented by the multiplication of two variables, differentiation, and the generation of some functions. In the terminology of analogue computers, the elements modelling these operations are usually called *computing units*.

Every general purpose analogue computer comprises, as a rule, several computing units of each type. Their kind and number determine its operational facilities, i.e. they define the class of mathematical systems that can be modelled on the given computer.

It is characteristic of general purpose analogue computers, that couplings between the elements of the system (i.e. between the computing units) are not permanent but are set up from case to case as required by the modelling operation to be performed.

General purpose analogue computers are most frequently used to model ordinary differential equations. They are therefore frequently designated as *differential analysers*. However, this name does not fully express their character, since computers of this type can also be used to model the most diverse systems of algebraic equations.

General purpose analogue computers are sometimes called "universal". This designation, however, is not justified, since the use of these computers is restricted to the modelling of a relatively narrow class of mathematical systems (systems with continuously variable quantities), even though they are highly versatile in this field.

In the majority of cases it is impossible to model a given abstract system directly. A suitable abstract model must first be found by means of various mathematical procedures. This model may contain, in an explicit form, only such operations as are realizable by the corresponding computing units. After having found a satisfactory mathematical

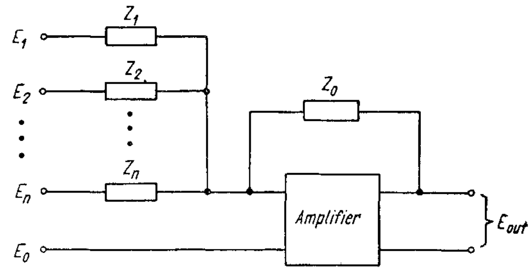

Fig. 6.5. Block diagram of computing amplifier

system, it will be possible to sketch a block diagram of the connections between the computing units and accordingly realize the corresponding pattern of connections in the computer.

Modelling proper is thus preceded in analogue computers by a pair of modelling operations with the aid of abstract recources. This kind of modelling is termed *program preparation for analogue computers.* The setting up of the couplings between computing units is then called the *programming of the analogue computer.* This kind of programming must on no account be confused with the programming of digital computers (see Chapter 7), which is quite a different matter. When concerned with analogue computers, it is therefore preferable to speak of the *preparation of computing nets.*

Older types of analogue computers used to be made up of mechanical systems. Later models employ almost exclusively electronic systems (valves or transistors).

The basic element of an electronic analogue computer is the *computing amplifier* (Fig. 6.5) whose behaviour (e.g. addition, integration, etc.) depends on the type of the impendances $Z_0, Z_1, \ldots, Z_n$. For this reason we do not speak in the case of electronic analogue computers of the number

of adders, integrators, etc., but of the number of computing amplifiers. According to this number we sometimes distinguish between *small* (with up to 15 amplifiers), *medium* (15 to 50 amplifiers) and *large* (with more than 50 amplifiers) general purpose analogue computers.

6.5 Computing Units

In order to enable readers, who are not familiar with the problem of analogue computers, to visualize their operation we present in Fig. 6.6 the principles of some computing units in a simplified form.

Fig. 6.6a depicts a *differential gear* (like the one used in the construction of motor cars) which can serve as the model of the algebraic sum y of two variables, x_1 and x_2. The angle of rotation of one shaft corresponds to the value of one input variable, the angle of rotation of the second shaft to that of the other input variable. The angle of rotation of the whole differential cage represents half the sum of the input variables. If we transfer this angle of rotation to another shaft via a pair of gear wheels having a gear ratio of 1 : 2 (i.e. a constant multiplier or scaler), we obtain the sum $y = x_1 + x_2$.

Fig. 6.6b illustrates the principle of the *wheel and disc integrator*. This consists of a disc rotated by a shaft and a small friction wheel connected with another shaft. The angle of rotation of the disc (quantity x_2) corresponds to the value of the independent variable, the radial distance of the friction wheel represents the value of the function to be integrated (x_1), and the angle of rotation of the friction wheel expresses the value y of the definite integral within the corresponding interval of the independent variable. The wheel and disc integrator thus models the relation

$$y = \int_a^b x_1 \, dx_2 \, .$$

Fig. 6.6c shows the circuit diagram of a simplified *electrical integrator* (an integrating circuit). As can be seen, this integrator is remarkably simple. It consists solely of a resistor R and a capacitor C. In electrical computing units, the independent variable is always represented by the time t, and this is one of their disadvantages. The input voltage x corre-

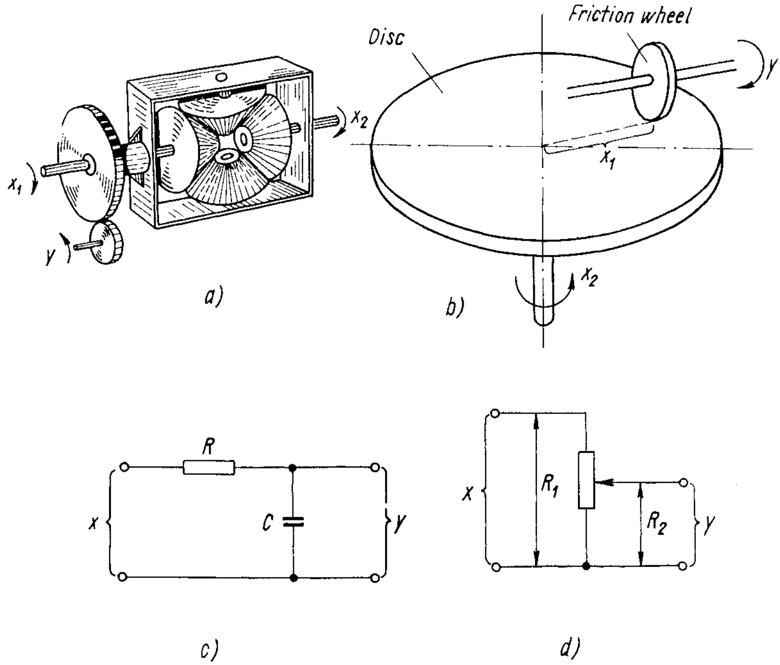

Fig. 6.6. Principle of some analogue computing units

a) Mechanical adder. b) Mechanical integrator.
c) Electrical integrator. d) Electrical scaler.

sponds to the function to be integrated, the output voltage y to the value of the integral limited by the corresponding time interval. The integrating circuit models the relation

$$y = \frac{1}{RC} \int_{t_1}^{t_2} x \, \mathrm{d}t \, .$$

In this case, the actual value of the integral is obtained by multiplying the output voltage y by the constant RC.

In Fig. 6.6d we present a simple *electrical scaler*. This is a resistor with a tapping, which may be adjustable (a potentiometer). The ratio of the input voltage x to the output voltage y is equal to the ratio of the corre-

sponding resistances R_1 and R_2, so that this circuit models the relation

$$y = \frac{R_2}{R_1} x .$$

The circuit thus performs a multiplication by the constant R_2/R_1.

6.6 THE PREPARATION OF COMPUTING NETS

In the foregoing sections we acquainted the reader with the principle of general purpose analogue computers and outlined the method of operation of some computing units. With the aid of a few simple examples we shall now illustrate the method whereby computing nets are assembled. In this process we shall assume that the only computing units at our disposal are adders, scalers, integrators, and some function generators. Their schematic symbols are presented in Fig. 6.7.

Let us first consider the modelling of the simple function

$$y = x^2 \tag{6.2}$$

over the interval from $x = a$ to $x = b$ (where $a < b$). Since we have no computing unit for the direct modelling of Eq. (6.2), we must first find a mathematical model which we shall be able to simulate in the computer. For this purpose let us first differentiate Eq. (6.2). We obtain the equation

$$\mathrm{d}y = 2x \,\mathrm{d}x . \tag{6.3}$$

If we introduce a new variable $z = 2x$, substitute it in Eq. (6.3) and integrate the right-hand side over the given interval of the independent variable x, we have the two equations

$$\begin{aligned} y &= \int_a^b z \,\mathrm{d}x \\ z &= 2x . \end{aligned} \tag{6.4}$$

We may say that the system (6.4) is a model of the behaviour of system (6.2). As opposed to system (6.2), however, the system (6.4) can be mod-

elled with the aid of the computing units available. The first equation of system (6.4) can be modelled by an integrator, the second by a scaler for $K = 2$. We now sketch the block diagram (i.e. the abstract model)

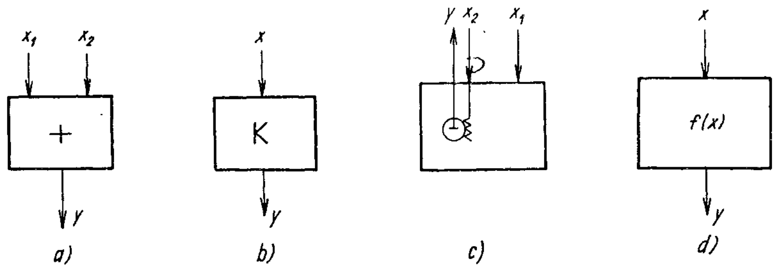

Fig. 6.7. Schematic symbols of analogue computing units

a) Adder: $y = x_1 + x_2$ c) Integrator (mechanical): $y = \int_a^b x_1 \, dx_2$

b) Scaler: $y = kx$ d) Function generator: $y = f(x)$

of the structure of the corresponding computing net (Fig. 6.8) and accordingly set up the required interconnections between the computing units in the computer.

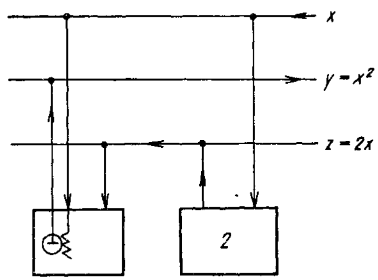

Fig. 6.8. Abstract model of structure of a computing net for system (6.4)

Now let us consider a system containing trigonometrical functions, e.g.

$$\begin{aligned} y &= \sin x \\ z &= \cos x \, , \end{aligned} \tag{6.5}$$

which we want to model over the interval from $x = 0$ to $x = 2\pi$. Let

us again differentiate both equations, so that we obtain

$$\begin{aligned} \mathrm{d}y &= \cos x \, \mathrm{d}x \,, \\ \mathrm{d}z &= -\sin x \, \mathrm{d}x \,. \end{aligned} \tag{6.6}$$

Introducing the substitution (6.5) into (6.6) and integrating over the required interval, we get

$$\begin{aligned} y &= \int_0^{2\pi} z \, \mathrm{d}x \,, \\ z &= \int_0^{2\pi} - y \, \mathrm{d}x \,. \end{aligned} \tag{6.7}$$

The system (6.7) can be modelled by two integrators as shown in Fig. 6.9.

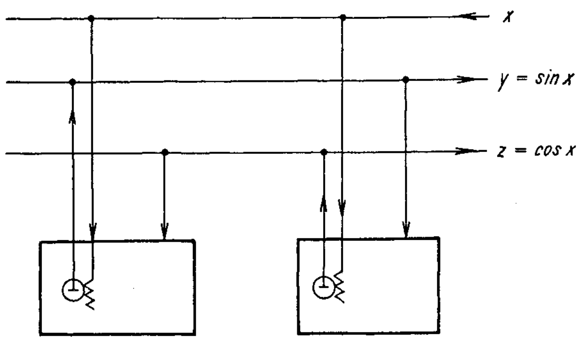

Fig. 6.9. Abstract model of structure of a computing net for system (6.7)

Now let us show how to model the product of two independent variables, i.e. the function

$$y = x_1 x_2 \,. \tag{6.8}$$

It is easy to prove that, for instance,

$$(x_1 + x_2)^2 - (x_1 - x_2)^2 = 4x_1x_2 \,.$$

Hence

$$x_1 x_2 = \tfrac{1}{4}[(x_1 + x_2)^2 - (x_1 - x_2)^2] \,. \tag{6.9}$$

Using the structure of the computing net presented in Fig. 6.8, which models the operation of raising a quantity to the second power, we can model the relation (6.9) directly. The corresponding abstract model of a computing net for the relation (6.9) is illustrated in Fig. 6.10.

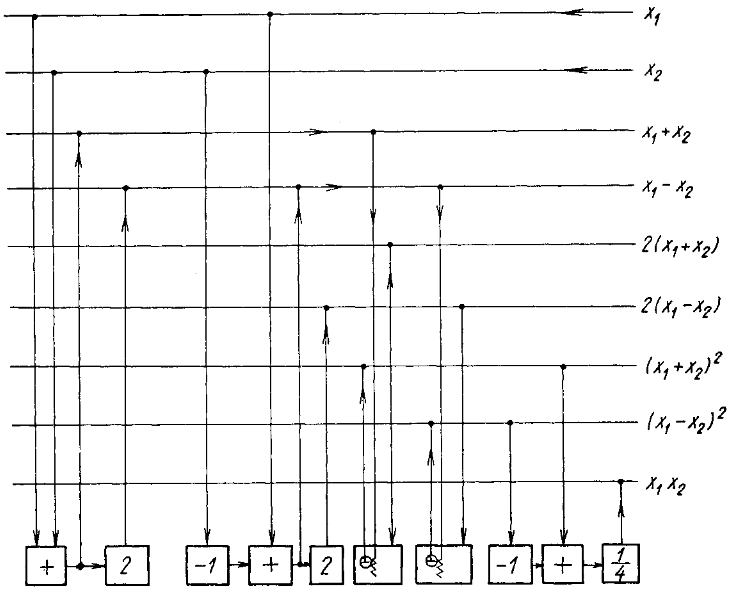

Fig. 6.10. Abstract model of a computing net for the multiplication of two variables according to relation (6.9)

Let us finally present an example of how to model a simple differential equation, namely

$$\frac{d^2y}{dx^2} + 5\frac{dy}{dx} - 2y = \log x\,, \tag{6.10}$$

assuming that a logarithmic function generator is available. Introducing the substitutions

$$\frac{dy}{dx} = z \quad \text{and} \quad \frac{d^2y}{dx^2} = \frac{dz}{dx} = w$$

into Eq. (6.10), we obtain a mathematical system which lends itself to direct modelling on the analogue computer, namely

$$
\begin{aligned}
y &= \int_a^b z \, \mathrm{d}x \,, \\
z &= \int_a^b w \, \mathrm{d}x \,, \\
w &= 2y - 5z + \log x \,.
\end{aligned}
\tag{6.11}
$$

The abstract model of a computing net for system (6.11) is presented in Fig. 6.11.

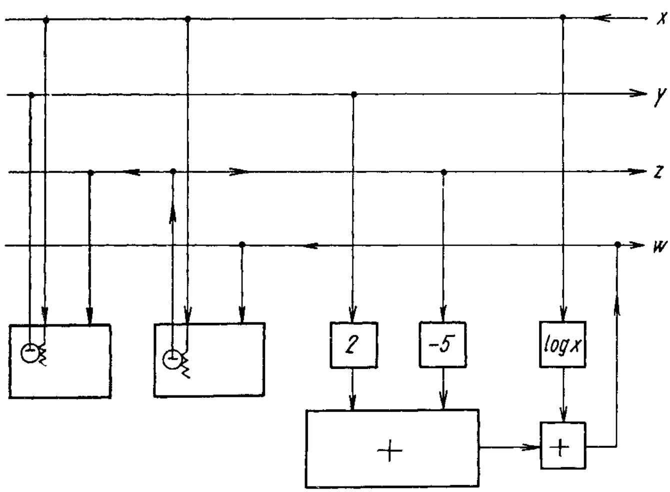

Fig. 6.11. Abstract model of a computing net for system (6.11)

6.7 Possibilities of Application

As already mentioned, analogue computers are not universal aids to modelling, and their use is confined to the modelling of mathematical systems containing continuous variables. Another restric-

ting factor in this field is the number and type of computing units and computing amplifiers available.

Moreover, yet another fact must be taken into account. The accuracy of modelling in analogue computers is limited owing to unavoidable inaccuracies in the manufacture of computing units that can never be totally eliminated. *Modelling errors* are usually in the range from 0.01 to 5%. If we want to achieve a better accuracy, we cannot avoid the use of digital computers, to which the following chapter is devoted.

Many good books have been written on analogue computers. Readers who want to get more closely acquainted with these aids to modelling are referred to the monographs listed under [C13, C20].

CHAPTER 7

DIGITAL COMPUTERS

At the present, digital computers are the most important aids to modelling. For the time being, no other devices can fully compete in this field with the facilities they provide. In some cases, modelling would be quite impossible without the aid of digital computers. At the same time, digital computers will be seen to be still in the stage of rapid development, manifesting itself by the ever-widening field of their capabilities. These are the reasons why we devote a separate chapter of this book to digital computers. We must remember, however, that the scope of this book does not permit us to deal with their construction in detail. We are chiefly concerned with presenting the digital computer as a modelling aid. We shall therefore give only a general explanation of their function, a summary of their basic properties, and the methods by which various systems can be modelled in them. In the course of our exposition we shall currently refer to literary sources in which the corresponding passages are elaborated in greater detail.

7.1 Basic Properties

Let us recall (see Sec. 6.6) that in general purpose analogue computers the mathematical system is modelled with the help of suitably coupled computing units, each of which models a single mathematical operation involving continuous variables.

The fundamental difference between analogue and digital computers is that, in the latter, we model operations with numbers expressed to a certain (finite) number of significant places. We are thus concerned with operations involving discrete quantities. In this field it is possible directly to model the most diverse arithmetical and logical operations,

but not, for instance, integration, continuous functions, etc. On the other hand, it can be shown that the behaviour of all such systems that cannot be directly modelled in digital computers can always be modelled in them with any desired accuracy by a time sequence of numerical operations. The attainment of the desired accuracy is then only a question of time and money.

The fact that mathematical systems can be modelled in digital computers with any desired accuracy constitutes one of their basic advantages as compared with analogue computers, the precision of which is always limited by inaccuracies in the computing units. Another remarkable property of digital computers is their versatility as far as modelling is concerned. Even though their proper province is the modelling of systems involving discrete quantities, systems with continuous quantities can be modelled in them, as already stated, with any desired accuracy.

7.2 ALGORITHMS

As already mentioned, digital computers are capable of directly modelling merely some numerical operations. These operations will be called the *basic operations* of the corresponding digital computer. They usually include the elementary arithmetical operations, i.e. addition, subtraction, multiplication, division, and shifting of digits, and some simple logical operations, such as conjuction, disjunction, negation, etc. (see Chapter 8).

More complicated arithmetical or logical operations, and operations involving variable quantities, are modelled by performing the basic operations in a certain sequence, called an *algorithm*.

In general, every precise instruction which uniquely determines the procedure leading from the initial information to the sought-for resulting information is an *algorithm*.*) It is divided into individual *steps* (operations), each of which must be realizable. The algorithm is characterized primarily by the following properties:

---

*) It should be noted that the definition of the algorithm presented above is not the only possible one. Other approaches to the definition of this concept will be found in current literature.

1. The algorithm must be unique. We sometimes speak, in this connection, of the determinateness of the algorithm. This means that every state of the algorithmic process uniquely determines the next step, and that after a finite number of steps there always follows a step that prescribes the end of the algorithm.

2. The algorithm may start from data that are, within certain limits, variable. Due to this property the same algorithm can be used for solving not only a single problem, but all problems of a certain class.

3. The algorithm always aims at the attainment of a definite goal.

The number of steps included in an algorithm may sometimes be so large as to make it *practically impossible* to attain a result. However, the boundary between practically realizable and impracticable algorithms is relative and is pushed ever farther as the result of the steady progress in computer design. The theory of algorithms therefore introduces the concept of the *abstraction of potential realizability*. This concept does not consider the real limits of our possibilities, but only the question of whether an algorithm exists or not.

The introduction of the abstraction of potential realizability is of importance not only to the investigation proper of the existence of algorithms, but also to the examination of initial, final and other information forming the object of algorithmic processing. We may thus consider sequences of words of any finite length, even though it might be impracticable to write them down.

Objects that can be constructed and examined within the framework of the abstraction of potential realizability are called *constructive objects*. They do not include objects investigation whose involves the abstraction of actual infinity, such as irrational numbers, geometrical points, etc.

An algorithm that is to be modelled by a digital computer must be adapted to the basic operations of this computer and must be practically realizable in the sense of the technical parameters of the computer (operating speed, storage capacity, speed of input and output units, etc.). In this sense we usually no longer speak of the algorithm, but of the program for the given computer. The algorithm is thus a broader notion, whereas the *program* is regarded as an algorithm already processed for a particular digital computer.

The sequence prescribed by the algorithm for the performance of individual operations depends frequently on whether the result of a particular operation satisfies or does not satisfy a condition specified in advance (e.g. whether it is positive or negative, larger or smaller than a given number, etc.). In such cases we speak of *conditional transfer* or *conditional jump operations*. The task of every operation of this kind is to determine uniquely the next operation (to find the sequel) according to whether the result of the foregoing operation satisfied a certain condition given in advance. If this condition is satisfied, the process continues in the normal manner (i.e. by the operation which is the next in the given sequence of operations). If the condition is not satisfied, a transfer is made to another point in the operational sequence.

It is true that a digital computer performs only numerical operations, but it is up to us how we interpret these numbers, i.e. what kind of input and output mapping we use for modelling. If we interpret the numbers, for instance, as the stimuli and responses in biological or psychological systems, we can model the behaviour of these systems in digital computers. If the numbers are interpreted as elements of some language, we can just as well model linguistic systems.

Algorithms can be expressed by various means. One of these is the *verbal description* which, although not very clear, is nevertheless important in some instances (particularly in psychological and biological systems).

Different *algebraic methods* can also be used to express algorithms. Among these we should like to mention Lyapunov's operator method of recording algorithms. Its principle consists in that the operations are written down in conventional symbols in a line, one next to the other. Conditional transfer operations are marked by signs referring to the place to which to transfer when the condition, supervised by the corresponding operation, is not fulfilled. Normal operations are usually designated by capital letters $A, B, \ldots$, conditional transfer operations by small letters $p, q, \ldots$, and references to other places by pairs of equally numbered vertical arrows. The referring (output) arrow points upwards, the arrow referred to (input) points downwards. The symbolic model of an algorithm presents, for instance, the following aspect:

$$\overset{3,5,6}{\downarrow} A\, B\, p \overset{1}{\uparrow} q \overset{2}{\uparrow} D \overset{4,7}{\downarrow} E\, r \overset{3}{\uparrow} \overset{1}{\downarrow} \bar{q} \overset{4}{\uparrow} r \overset{5}{\uparrow} \overset{2}{\downarrow} F\, s \overset{6}{\uparrow} r \overset{7}{\uparrow} . \tag{7.1}$$

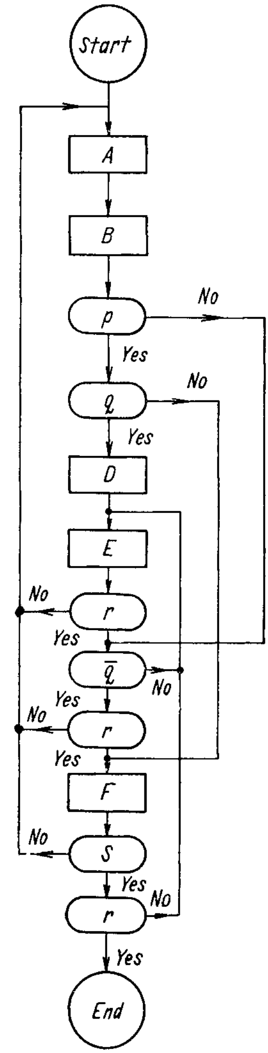

Fig. 7.1. Block diagram of algorithm (7.1)

Even though the operator method is economical and well-suited to print, it is not always sufficiently clear when working with algorithms. Preference is therefore frequently accorded to the *graphic method* used under the name of *block diagram* or *flow chart* of program. With this method, normal operations are inscribed symbolically into rectangles, whereas conditions for conditional jump operations are inscribed in ovals. The start (and end) of the algorithm is designated by a circle with the inscription "*start*" (or "*end*", respectively). The rectangles, ovals and circles are interconnected according to the structure of the corresponding algorithm. Only a single connecting line issues from every rectangle. Two connecting lines go out from every oval, one marked "*yes*" (to be followed when the condition indicated in the oval is fulfilled), the other "*no*" (to be followed when the corresponding condition is not fulfilled). Every block may be entered by several connecting lines.

To illustrate our case we show, in Fig. 7.1, a graphic model of the algorithm presented in (7.1). The advantage of block diagrams consists in their clarity and in that it is possible to inscribe individual operations explicitly in the corresponding blocks instead of using symbols such as A, B, etc.

7.3 EXAMPLES OF ALGORITHMS

Algorithms are very frequently encountered in everyday life without our being aware of this fact. When multiplying two numbers consisting of several digits each, for instance, we base our procedure in principle on two operations: the multiplication of two decimal digits and the addition of two decimal digits. These operations are carried out in a certain order which does not depend on the actual values of the numbers to be multiplied. We are thus concerned with an algorithm. We learnt it very thoroughly at our primary school and since then we have kept its model in mind. We can recall it whenever necessary and then carry out the multiplication quite mechanically.

Another example of an algorithm is the computation of some value according to a mathematical formula. For instance, we are required to model by an algorithm the behaviour of a set of two linear algebraic

equations in two unknowns:

$$a_1x + b_1y = c_1$$
$$a_2x + b_2y = c_2\,, \tag{7.2}$$

where the coefficients a_i, b_i and c_i $(i = 1{,}2)$ are regarded as inputs and the unknowns x and y as outputs. It is obvious that the system (7.2) can be modelled symbolically (provided that $a_1b_2 - a_2b_1 \neq 0$) so that the relation between responses and stimuli is expressed explicitly:

$$x = \frac{b_2c_1 - b_1c_2}{a_1b_2 - a_2b_1}\,, \qquad y = \frac{a_1c_2 - a_2c_1}{a_1b_2 - a_2b_1}\,. \tag{7.3}$$

The relations (7.3) can be modelled directly by an algorithm based on subtraction, multiplication and division. The algorithm may consist, for instance, of the following sequence of operations: $K_1 = a_1b_2$, $K_2 = a_2b_1$, $K_3 = K_1 - K_2$, $K_4 = b_2c_1$, $K_5 = b_1c_2$, $K_6 = K_4 - K_5$, $K_7 = a_1c_2$, $K_8 = a_2c_1$, $K_9 = K_7 - K_8$, $x = K_6 \div K_3$, $y = K_9 \div K_3$. Let us note that this sequence expresses the same behaviour as the systems (7.2) and (7.3). Compared with the algorithm for multiplication presented in our first example, we are now concerned with an algorithm at a higher level, since it utilizes the multiplication of two numbers (which may consist of several digits) as a basic operation.

We might find algorithms at still higher levels in sets of linear algebraic equations. This happens mainly when handling equations in matrix form. The values of every unknown are then expressed by the quotients of the values of two determinants, where the evaluation of the determinants can be considered as a basic operation. Let us note that in this connection we are actually concerned with expressing the same algorithm at a different resolution level.

Quite a different method of modelling by means of an algorithm will be demonstrated on the simple system

$$x = \sqrt{N}\,, \tag{7.4}$$

where N is the input and x the output. System (7.4) can be modelled to

an arbitrary accuracy by a different system:

$$x_{n+1} = \frac{1}{2}\left(\frac{N}{x_n} + x_n\right), \quad n = 0,1, \ldots, \tag{7.5}$$

where N and x_n are inputs and x_{n+1} is the output.

The coarse structure of system (7.5) is shown in Fig. 7.2; the input p, depicted by a dashed line, will be disregarded for the time being. It will be noted that the system incorporates a feedback coupling which brings the values of the outputs x_{n+1} back to the input where they are

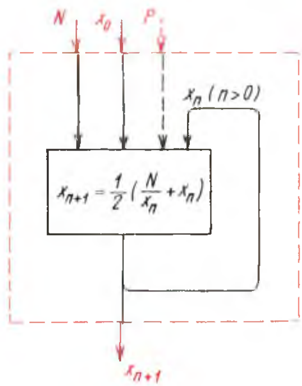

Fig. 7.2. Coarse structure of system (7.5)

interpreted as x_n. The system attains the equilibrial state (see Sec. 4.7) when $x_{n+1} = x_n$. In this case we get (after substituting in Eq. (7.5) and rewriting) $x_n = \sqrt{N}$. If, however, $\sqrt{N}$ were an irrational number (e.g., $\sqrt{2}$), which cannot be expressed by a finite number of digits beyond the decimal point, the system of Fig. 7.2 would never attain the equilibrial state. If, however, when modelling the system (7.4), we content ourselves with a certain maximum error p, the system of Fig. 7.2 may be regarded as such that an error smaller than p introduced by means of a separate input P would cause the system to be artificially brought to the state of equilibrium. The value of p represents the upper limit of the permissible error, whereas the actual error p' is given by the relation

$$p' = \frac{N}{x_n} - x_n .$$

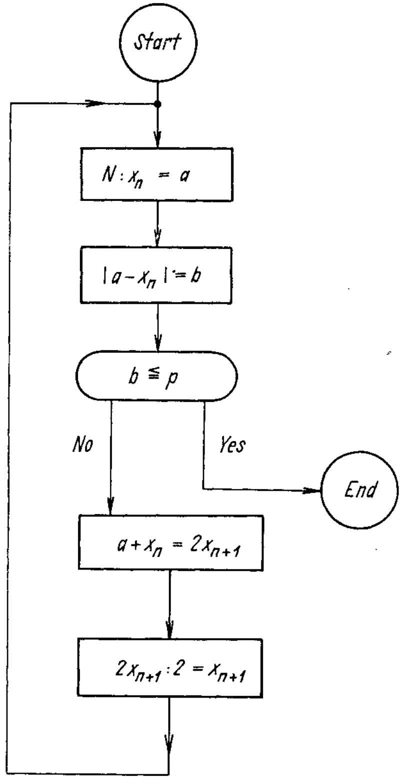

Fig. 7.3. Symbolic model of system (7.5) with inaccuracy p

Thus our procedure involves the comparison of the values of p and p' inside the system. If $p' \leqq p$, the system is automatically brought to the equilibrial state, i.e. the appropriate value of x_n appears permanently in the output.

Fig. 7.3 shows the block diagram (or flow chart) of an algorithm which models the system (7.5) with an inaccuracy p. For the sake of comparison we also give a representation of this algorithm by the operator method, writing out all the operations in full and separating them by commas.

$$\overset{2}{\downarrow} N : x_n = a,\ |a - x_n| = b,\ b \leqq p \overset{1}{\uparrow} End \overset{1}{\downarrow} a + x_n = 2x_{n+1},$$
$$2x_{n+1} : 2 = x_{n+1} \overset{2}{\uparrow}$$

Let us present, as a further example, the behaviour of an animal from the point of view of the creation and extinction of a single conditioned reflex (see Sec. 11.1). In this instance we are concerned with two stimuli and one response. One of the stimuli always leads to the corresponding response, the other one only under a certain condition. This condition consists in the accumulation of a certain quantity inside the system until it attains a specified value. The factors participating in this accumulation are chiefly the kind and the ordinal position of the stimuli and, in part, random effects of which the source lies inside the system. Let us note that the algorithm (7.1), which we used in Sec. 7.2 to illustrate different methods of expressing algorithms, also models the creation and extinction of conditioned reflexes. For the time being we are not going to enlarge upon the significance of the individual operations, since we shall return to this matter at a later stage.

If it is possible to express the creation and extinction of a single conditioned reflex by an algorithm, it will also be possible to use this method for expressing several conditioned reflexes, or conditioned reflexes created on the basis of other conditioned reflexes, etc. Algorithms can thus be used to express even the very complicated behaviour of animate systems. The means for realizing such algorithms are provided by the digital computer.

7.4 Algorithmic Procedure

To facilitate understanding of the structure and operation of digital computers, let us first show how algorithmic computational procedures, used to model mathematical systems, can be realized without digital computers.

In this case, the computation process is performed by a human being – let us call him the *computist*. The computist has a *desk calculator* and certain basic *information* (see Fig. 7.4). The desk calculator performs the four basic arithmetical operations. The basic information consists of a *set of instructions* and a *data sheet*. The set of instructions contains, in some form, the *complete algorithm* required for the solution of the given problem. From the data sheet the computist takes the *initial values* of

the problem and enters in it various intermediate values as well as the final results.

The algorithm contained in the set of instructions must be formulated so as to consist only of operations that can be performed on the desk calculator. In addition, every operation must be accompanied by a unique instruction stating which numbers are concerned, i.e. from which spaces in the data sheet the corresponding numbers must be taken.

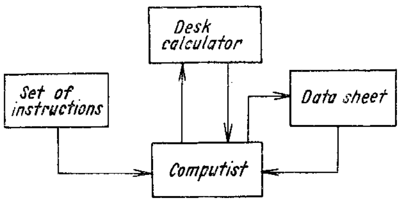

Fig. 7.4. System for realizing computational procedure

The computist proceeds by reading the individual instructions in succession and executing them with the aid of the data sheet and the desk calculator. Every instruction states uniquely the kind of operation and the number on which the operation is to be carried out. Thus the computist need not understand the contents of the corresponding algorithm; he can still carry it out provided, of course, that he consistently obeys the given instructions. There is thus no reason why we should not model the computist in the function described above by an inanimate system.

The idea of modelling a system such as that of Fig. 7.4 by an inanimate system was hit upon by an English mathematician, CHABLES BABBAGE, as long ago as 1834. To the end of his life (he died in 1871) he tried very hard to realize his idea. However, he succeeded only in part, chiefly owing to a lack of financial means and because of the imperfect technical resources of his time. After his death, his brilliant idea, which had originally aroused a great sensation, fell into oblivion. The digital computer as envisaged in principle by BABBAGE was not realized until World War II, i.e. more than a hundred years after the advent of the original idea.

7.5 DIGITAL COMPUTER COMPONENTS

As already mentioned at the conclusion of the preceding section, the digital computer constitutes, in principle, a model of the system illustrated in Fig. 7.4. An essential feature of the digital computer is that it fully models the actions of a computist by an inanimate system.

Every digital computer comprises five basic units: *store, arithmetic unit, control unit, input unit*, and *output unit*.

The *store* of a digital computer corresponds to the basic information in the system of Fig. 7.4. This is a device in which the whole program (or set of instructions) can be stored together with the required initial data, and from which the instructions and the numbers, which form the objects of the individual operations, can be obtained as required. In the course of the computation, various intermediate results are recorded in the store, and so are the final results. Just as the data sheet is divided into individual spaces, so the store of a digital computer is divided into individual storage cells. Every cell has its serial number, termed the *address*. Every storage cell can hold only one number. In this connection we must remember that the digital computer works with numbers which always have a given maximum number of digits.

The *arithmetic unit* of a digital computer corresponds to the desk calculator in Fig. 7.4. In principle, its task is the same. It performs simple arithmetical and logical operations on the numbers inserted in it. The arithmetic unit does not decide, which operation is to be carried out on the corresponding numbers. It obeys the instructions arriving in it from the control unit.

The *control unit* is the most interesting and most important part of the digital computer, since it plays the role of the computist (see Fig. 7.4). The control unit successively releases instructions from the store. According to these instructions it then takes the appropriate numbers from the store (the addresses of the corresponding cells being contained in the instruction) and inserts them in the arithmetic unit. At the same time it adjusts the arithmetic unit in accordance with the instruction so that it performs the required operation. It then records the result of the operation in the location whose address is given in this connection by the instruction. After having completely carried out one instruction, the

control unit automatically takes from the store another instruction, i.e. the next instruction in the sequence to be followed according to the given program.

The digital computer also contains an *input* and an *output unit*. These are devices which translate, on the one hand, the pertinent data from human language into the "language" of the computer (input unit), on the other hand from the computer "language" (the machine script) into a form we can understand (output unit). These units will not be found in Fig. 7.4. They may, however, be envisaged as follows: The input unit represents the person (or institution) from whom the computist receives the basic information together with the necessary explanation, whereas the output unit represents the person (or institution) to whom the computist hands over the results in an intelligible and legible form, if necessary with an explanation.

7.6 INSTRUCTIONS

The *instruction* is a basic element of the program, i.e. of the algorithm adapted to the given digital computer. It is expressed by a number, and in this form it defines uniquely a given elementary operation of the computer.

Every instruction consists usually of two parts: the *function part*, and the *address part*. The function part specifies, in a given digital code, the kind of operation to be performed; the address part gives the serial number of one or several addresses (see Sec. 7.5) which have a uniquely determined significance in connection with the given operation.

If the computer were to perform some elementary arithmetical operation (e.g. the addition of two numbers) directly, according to a single instruction, the latter would have to contain three addresses (two for the selection of the addends and one for storing the result). An operation can, however, also be controlled by several consecutive instructions. In such a case a single address is sufficient for each instruction.

We speak of single-address, two-address to five-address instructions (or computers), according to the number of addresses contained in the instruction. Computers built at the present are mostly of the single-

address type; two-address and three-address computers are less frequent, and four- and five-address computers are quite exceptional.

If two numbers are to be added in a single-address computer, three instructions must be used. The first instruction transfers one of the addends from the store to the arithmetic unit, the second instruction is used to transfer the second addend from the store to the arithmetic unit and to perform the addition of the two numbers. The third instruction inserts the sum in the store at the specified address.

Instructions are expressed in computers by the same code as are numbers. It is therefore possible to process them arithmetically. This circumstance is of extraordinary importance from the point of view of modelling, since it enables a program to be automatically transformed and thus permits even very complicated types of behaviour – such as learning, self-organization, etc. – to be modelled. It also forms the basis of *automatic programming*, where the computer is entrusted with part of the programming work.

In addition to the function part and address part which have already been mentioned, an instruction may contain further codes which characterize the particular features of the given computer. We are not going to discuss this matter any further; for a more profound study we recommend Ref. [C27].

7.7 THE PROGRAM

The *program* for a given computer is a set of precise instructions specifying how to perform the elementary operations of this computer in a certain sequence; it may be regarded as a model of the behaviour of all systems of a given type.

The restriction of the program to the elementary operations of a computer is a matter of only relative necessity. That is to say, subroutines are laid out for operations which are frequently required but are not among the elementary operations of the computer. These *subroutines* are deposed in a *program library* and can be used whenever needed. When setting up a program, operations for which subroutines are available for a given computer can be handled, in principle, in the same

manner as though they were elementary operations of the particular computer.

Any program can be modelled by an oriented graph. Every node of this graph corresponds to a single instruction and the oriented connecting lines between the nodes indicate how the individual instructions in the program follow upon each other. Either one (in case of unconditional transfer) or two (in case of conditional transfer) connecting lines emerge from every node, but any number of connecting lines may enter the node. In principle, this graph is equivalent to the block diagram or flow chart mentioned in Sec. 7.2.

The completion of the block diagram by no means concludes the preparation of the program. Addresses must first be suitably assigned to the individual instructions and the instructions then translated into the machine script. In this form the program can be fed to the computer.

Automatic programming systems have been worked out for some computers. Their importance consists in that they permit programs to be fed to the computer directly in a general form, i.e. with the aid of current algebraic and logic symbols. Addresses are assigned to the individual instructions and the instructions translated into the machine script by the computer itself. In such cases programming is very comfortable and rapid.

7.8 Computer Operation

The symbolic model of a typical digital computer is illustrated in Fig. 7.5 in the shape of a block diagram. The rectangles represent the basic units of the computer, the general properties of which were described in Sec. 7.5. The heavy black lines represent the bundles of signal paths which transmit the information that is being processed. The control signal paths are marked by light, green lines. The circles correspond to elements which open the required signal paths in dependence upon the control signals. These elements are called *gates* and in Fig. 7.5 they are denoted by symbols G_1 to G_5.

Modelling of a given algorithm in a digital computer always starts by inserting the corresponding program and the required data into the

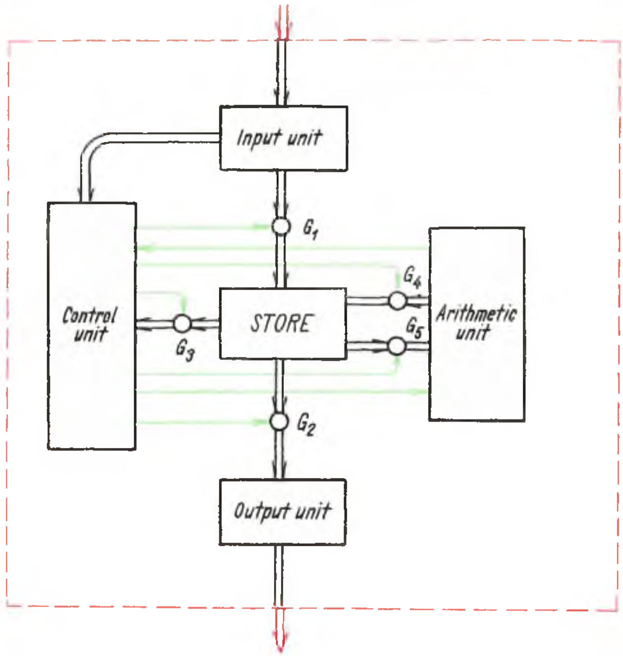

Fig. 7.5. Block diagram of digital computer

store of the computer by way of its input unit. The control unit ensures that the data are registered at the correct addresses. It does this by controlling the gate G_1 in the appropriate manner in accordance with information received from the input unit.

After having inserted all the required information in the store, the first instruction of the program must be fed from the input unit directly to the control unit. For this purpose the control unit is fitted with a small store capable of holding only one instruction. This store is usually termed the instruction register.

The *instruction register* occupies a very important position in the computer. It is the centre from which the operation of the whole computer is controlled according to the instruction stored in it.

Before starting the computer, more information must be inserted in the control unit, concerning the address from which to take the next

instruction of the corresponding program. The element used in the control unit to store this information is called sequence control register.

The *sequence control register* is characterized by containing, throughout the program, information on the address of the next instruction. Since normal operations are always assumed to be stored at successive addresses, the contents of the sequence control registerinc rease by unity after each normal operation. After a jump, however, the contents of the sequence control register are replaced by the new address increased by unity.

Now let us assume that the computer store already holds all the information needed, that the first instruction of the program has been inserted in the instruction register of the control unit, and that the sequence control reg'ster contains the address from which the next instruction of the program is to be derived. Under these assumptions the computer may be started, e.g. by depressing the START pushbutton. This action passes the initiative to the control unit, which causes the computer to perform the operation defined by the first instruction. During this step, control is exercised by the instruction register.

Normal operation consists of the numbers from the addresses specified by the instruction stored in the instruction register being transferred with the aid of gate G_5 to the arithmetic unit. At the same time the control unit causes the arithmetic unit to carry out the desired operation. With the help of gate G_4 the result of this operation is stored at the corresponding address in the store. Let us recall (see Sec. 7.7) that in single-address (or two-address) computers three (or two, respectively) partial instructions are required for the operation described.

As soon as a certain instruction has been carried out, the contents of the instruction register must be replaced by a new instruction. The selection of this instruction from the store is controlled by the control unit itself with the aid of gate G_3. If the prior instruction was a normal one, the control unit takes the next instruction from the address given by the sequence control register, the contents of the latter being, at the same time, increased by unity. If the prior instruction caused a jump in the program, the control unit takes the next instruction from the address given by the jump instruction, and the contents of the sequence control register are replaced by this new address increased by unity. With con-

ditional jump instructions, the jump depends on whether the preceding operation fulfilled a given condition. The control unit is informed of this by the arithmetic unit over a separate signal path shown in Fig. 7.5.

The control unit successively extracts the individual instructions from the store in the manner described, and controls the operation of the whole computer in accordance with these instructions. When it arrives at an instruction involving the output, it transfers the corresponding information from the given address via gate G_2 to the output unit. The latter then transforms this information into the desired form (print, punched cards, magnetic tape, etc.).

The program is always concluded by the STOP instruction, which stops the computer and signals the end of the program.

7.9 TIME-SHARING

Some modern digital computers are conceived so as to permit the concurrent processing of several programs. This feature is called *time-sharing*. From our point of view it is of interest chiefly because it bears, in several respects, a striking resemblance to the conception of some biological systems. In computers with provision for time-sharing we distinguish the computer proper from the accessory equipment. In the computer proper we include the arithmetic unit, the control unit, a low-capacity store with short access time, and a unit we have not considered so far – the *organizing unit*. The accessory equipment is taken to include, in particular, various input and output devices, and large-capacity stores.

The reasons for introducing the time-sharing facility are of a predominantly economic character. In normal computers appreciable differences exist between the speed of the basic computer and that of the accessory devices. Whenever an instruction is carried out which concerns some accessory device, the basic computer remains unused for a considerable time owing to its superior speed. Time-sharing eliminates this disadvantage by making the operation of the accessory units completely independent. These units obtain from the basic computer only the appropriate instruction, and this they carry out on their own, inde-

pendently of the basic computer. While this instruction is being performed, the basic computer is not blocked but is free to execute another program.

The basic computer is assigned to the individual programs by the organizing unit. The main task of the latter is to ensure that the individual programs do not get intermingled. In addition, it evaluates at every instant the situation of the individual programs. To each program it assigns a priority, i.e. a number which expresses how urgently the corresponding program requires the services of the basic computer at the given instant. At the same time it makes sure that the basic computer is always assigned to the program having the highest priority.

7.10 TURING'S MACHINE

In 1936, the English mathematician A. M. TURING (1912–1954) published a paper [C40] from which it follows that, in principle, every algorithm can always be modelled by another algorithm consisting of the elementary arithmetical operations only. TURING went still farther and showed that even much simpler operations suffice for modelling. He based his speculations on the abstract model of a trivial computer and proved that this computer was capable of modelling any algorithm.

A Turing machine represents an extreme as far as the small number of operations and their simplicity are concerned. It can be envisaged in various forms. Turing imagined his machine as consisting of an infinite tape divided into frames, a device capable of shifting the tape, as a result of a given stimulus, by one frame to the left or right, of a store capable of acquiring a finite number of states, of a recording device and of a readout device. He assumed that a computer conceived in this manner could perform only the following elementary operations: shift the tape by one frame to the left or right, record one out of two possible symbols in a given frame of the tape, read out or erase the symbol in a given frame, change the contents of the store, and stop.

Even though a Turing machine is extremely simple (the conception described is not the only possible one; others have also been suggested), it is of no practical value whatsoever. It can easily be shown that such

a computer would be substantially slower in solving various problems than a human being. Moreover, it would be unimaginably difficult to program.

Quite a different matter is the theoretical importance of the Turing machine. That is to say, the abstract model of a Turing machine served as the basis for the mathematical *theory of computable functions* which deals with the solvability of problems, i.e. which endeavours to define clearly and precisely the problems for which an algorithm exists that leads to their solution. The theory of computable functions may be regarded as an abstract model of the general theory of algorithms. Among other models let us mention, for instance, the *theory of recursive functions* and the *theory of normal (Markovian) algorithms*. For a more profound study of these theoretically very interesting and important problems, which we are not going to treat in this book, we refer our readers to the monograph listed under Ref. [C10].

7.11 PROBABILITY MODELS

In connection with modelling by digital computers let us mention, for the sake of completeness, a special class of models which would be of no practical importance but for the existence of digital computers (not necessarily universal ones). We are thinking of *probability models*.

The probability model of a given mathematical system is, in principle, a random process some of whose statistical properties (e.g. mean value, deviation, dispersion, distributive function, correlation function, etc.) are similar to certain properties of the given system.

In probability modelling we are thus concerned, in principle, with the realization of random processes of given properties. There are two methods of achieving this aim:

1) by directly creating the desired process,

2) by creating a simple random process with very accurate characteristic properties and transforming it into the desired process.

We usually employ the second method, which is more economical. The simple process used in this case as the basis may be represented, for

instance, by a sequence of the binary digits 0 and 1, which occur with equal probability $\frac{1}{2}$.

Random processes possessing precise characteristic properties are usually obtained by one of the following methods:

1) with the aid of physical models utilizing random physical phenomena (e.g., the decay of a radioactive substance, the Brownian movement, noise in resistors or electronic valves, etc.).

2) by means of algorithmic models, where a random sequence is obtained with the help of suitably defined arithmetical operations.

A really *random sequence of digits* can be obtained by the first method, which is mostly used in special-purpose computers. When using the second method, to which preference is usually given in general-purpose computers (where the program for the generation of random digits forms part of the complete program), we speak of *pseudo-random* sequences. It appears that random sequences obtained by arithmetical operations show a certain periodicity. The sequence thus repeats itself. When a suitable algorithm is chosen, however, it is possible to attain periods of such magnitude as to be fully satisfactory for all practical purposes.

Probability models serve as the basis for some special computation methods called *Monte Carlo methods*, which were devised by JOHN VON NEUMANN.

Monte Carlo methods can be used for solving many difficult mathematical problems, e.g. for the solution of differential and integral equations, matrix inversion, etc. Even when applied to simple problems, however, their use always calls for a large number of operations, since probability laws are valid only for large numbers of events. These methods are therefore not suited for use by the human computist. Their importance, however, is steadily rising with the increasing speed of digital computers.

CHAPTER 8

LOGIC NETS

The chapter on logic nets as aids to modelling has been included in this book for two main reasons. The first of these is that logic nets constitute universal modelling aids and can be very well used for modelling even some higher manifestations of the behaviour of psychological systems. With the help of such models, which are of outstanding clarity, it is often easier to understand certain types of behaviour. The second reason is that the theory of logic nets forms the basis of the modelling of neuron circuits (see Chapter 11) which is of importance both to cybernetics and to neurophysiology.

The extent and scope of this book do not permit the theory of logic nets to be treated in a unified manner. We shall, on the one hand, use logic nets to illustrate some general properties of systems, and on the other hand present methods for the synthesis of logic nets as models of behaviour. We shall complement our exposition by references to important literary sources for further study.

8.1 FUNDAMENTAL CONCEPTS

In the explanation to follow we shall regard as logic nets such determinate (physical and abstract) systems, in which every input as well as every output (see Sec. 2.7) can acquire only one out of two possible values, and which contains only elements whose inputs and outputs can also acquire only one of two possible values.*) Logic nets regarded in this manner are, in principle, models of relations occurring in so-called classical logic, i.e. *extensional and two-valued logic.*

*) In principle, many-valued logic nets are also possible. We confine ourselves here to two-valued nets because they are the ones most frequently used in practice.

If we consider the logic net as a cybernetic system (see Sec. 4.2), then every partial input or partial output of this system or of any of its elements will be the carrier of elementary signals, i.e. of signals with the information content of 1 bit. To distinguish between the two values of the signals mentioned, the magnitudes of which are of no interest to us, we shall use the traditional symbols of 0 and 1.

Let us assume that the logic net has in general p partial inputs and q partial outputs. The full variety at the input is then 2^p (see Chapter 4), the full variety at the output is 2^q. Let $x_1, x_2, \ldots, x_p$ designate the partial stimuli, and $y_1, y_2, \ldots, y_q$ the partial responses.

Every stimulus in a logic net (or a certain combination of the values of partial stimuli) can be expressed by a binary number of order p. If this number is written out in decimal notation, we speak of the *input identifier*. It is obvious that every stimulus in a given logic net is uniquely determined by its input identifier, and vice versa. In this chapter, the input identifier will be consistently denoted by the symbol i, the corresponding stimulus being denoted by the symbol $\mathbf{x}_i$ ($i = 0,1,\ldots, 2^p - 1$).

In a similar sense we may speak of an output identifier. For this we introduce the general notation j, the corresponding response being denoted by $\mathbf{y}_j$ ($j = 0,1,\ldots, 2^q - 1$).

The behaviour of a logic net and of all its elements can be described by the resources of logic algebra, of which more will be said in the following sections. In this connection we shall speak of *logic input (independent) variables* in place of partial stimuli, and of *logic output (dependent) variables* in place of partial responses.

Logic nets are divided, according to their behaviour, into combinatorial and sequential nets. In combinatorial nets the output variables are functions of the input variables only, whereas in sequential nets they are also functions of other (internal) variables which depend on the sequence in which the stimuli arrive.

8.2 THE SCOPE OF MODELLING

Before proceeding with the explanation of the properties of logic nets we must first delimit the class of systems that lend themselves to modelling by logic nets.

First of all, it is clear that logic nets can be used to model all types of discrete determinate systems. It is only necessary that the full input (or output) variety be equal to or larger than the input (or output) variety of the original.

However, if logic nets are capable of modelling discrete systems, they can also be used to model the behaviour of the corresponding elements. Let us model the behaviour of elements $a_1, a_2, \ldots, a_n$, which constitute the universe **A** of system **S**, by the logic nets $b_1, b_2, \ldots, b_n$, which form the universe **B**. If we introduce between the elements of universe **B** the same couplings as those existing between the elements of universe **A**, we get a logic net of higher order which is, of necessity, a model of system **S**.

The modelling of continuous systems by logic nets is somewhat more difficult and less convenient. But even in this field modelling will be possible in the majority of cases. This follows from WHITTAKER'S well-known sampling theorem enunciated in 1915, which says that a continuous function with a frequency spectrum having an upper frequency limit f_{max} can be accurately expressed by a finite number of its values sampled at time intervals of

$$t = \frac{1}{2f_{max}}.$$

The assumption of a limited frequency spectrum is always fulfilled in physical systems; there are only some abstract systems in which it is not fulfilled. It is also clear that the value of a function can always be expressed by a finite quantity of binary numbers, their number depending on the precision required.

Since logic nets are capable of modelling arithmetical operations, they can also be used to generate sequences of pseudo-random numbers (see Sec. 7.10). Thus it is possible to model even random systems by logic nets.

In conclusion, we can now say that *logic nets are universal modelling aids, with the reservation that they are incapable of modelling continuous abstract systems with an unlimited frequency spectrum.*

In this book we are interested in logic nets chiefly in their role as models of psychological and of some biological systems. However, we also

want by their aid to elucidate some properties concerning general systems. Considering the scope of modelling by logic nets outlined above, such an approach appears as possible and useful.

8.3 Simple Logical Functions

A logical independent variable x can acquire only two values, denoted according to our convention by 0 and 1 respectively. According to the value 0 or 1 which we assign to each value of the independent variable, we obtain different *logical functions of a single independent variable.* In this case there exist only four such functions, which we denote by f_0, f_1, f_2 and f_3*) respectively. Expressed in tabular form, they are:

x	f_0	f_1	f_2	f_3
0	0	1	0	1
1	0	0	1	1

It will be seen that $f_0 = 0$ and $f_3 = 1$ are independent of x. Furthermore we have $f_2 = x$. This function is called *assertion*. The most interesting for our purposes is the function f_1 (printed in red) which to $x = 0$ assigns the value 1 and, conversely, to $x = 1$ the value 0. This is termed *negation* and is usually denoted by a bar over the letter x. Thus, $f_1 = \bar{x}$. Our discussion will be based chiefly on this function; let us therefore express it in tabular form again:

x	$\bar{x}$
0	1
1	0

Now let us consider the logical functions of two logical independent variables denoted by x_1 and x_2 respectively. In this case there exist altogether 16 different functions, listed in the following table:

---

*) To simplify our notation, functions will in this chapter be denoted without their arguments.

x_1	x_2	f_0	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}
0	0	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
0	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
1	0	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1

It will be noted that some of the functions listed are either trivial, or depend upon only one variable. These are the functions $f_0 = 0, f_3 = \bar{x}_1$, $f_5 = \bar{x}_2, f_{10} = x_2, f_{12} = x_1$, and $f_{15} = 1$. The remaining ten functions (printed in red) depend on both variables These functions are designated by special names and algebraic symbols, but these have not yet been generally agreed upon. Let us therefore present a list of frequently used symbols and names for these functions:

$f_1 = x_1 \downarrow x_2$ (Peirce function, or rejection)
$f_2 = x_1 \nrightarrow x_2$ (inhibition, or sub-junction)
$f_4 = x_1 \nleftarrow x_2$ (reversed inhibition)
$f_6 = x_1 \not\equiv x_2$ (non-equivalence)
$f_7 = x_1 \mid x_2$ (Sheffer stroke, or non-conjuction)
$f_8 = x_1 x_2$ (conjunction, or logical product)
$f_9 = x_1 \equiv x_2$ (equivalence)
$f_{11} = x_1 \rightarrow x_2$ (conditional implication, or inclusion)
$f_{13} = x_1 \leftarrow x_2$ (reversed implication)
$f_{14} = x_1 + x_2$ (disjunction, or logical sum)

Let us note that among the functions listed there are some pairs of functions which differ only by the independent variables being interchanged and they are thus substantially equal. These are the pairs $f_2 - f_4$ and $f_{11} - f_{13}$.

Two logical independent variables thus generate only eight new different functions. It is interesting and very important that these eight functions together with negation fully suffice to express any logical function of an arbitrary (but finite) number of logical independent variables. We may go even further: *Any logical function of an arbitrary number of logical independent variables can be expressed by using only some of the functions listed.*

The problem of the smallest possible sets of simple logical functions sufficient to express general logical functions has been very thoroughly examined by the methods of symbolic logic. The conclusions arrived at are very surprising. It appears that the functions listed above are not equivalent in the sense mentioned, i.e. that not all of them offer the same possibilities for expressing general functions.

Two of the functions mentioned occupy a special position – the *Peirce function* f_1 and the *Sheffer stroke* f_7. Both functions are characterized by each of them by itself being sufficient to express general logical functions. None of the other functions possesses this property. We must therefore use pairs or triplets of such functions. In some cases the pairs of functions required are, for instance: *negation-conjuction, negation-disjunction, negation-inhibition, negation-implication*, etc. In other cases we must use triplets of functions, e. g. *equivalence – non-equivalence – conjunction, equivalence – non-equivalence – disjunction*, etc.

By deciding to start from a given set of simple logical functions, we have actually laid the foundations of a distinct logic algebra which has its characteristic laws. We may formulate a set of axioms for the corresponding algebra and then, based on them, deductively construct the whole algebra. It is thus possible to construct a Sheffer or Peirce algebra, an algebra based on negation and implication, etc.

Of the greatest importance to the theory of logic nets is *Boolean algebra,* which employs negation, conjunction and disjunction. The name Boolean algebra is used in honour of the Irish mathematician George Boole (1815–1864), one of the founders of modern symbolic logic.

At first sight it seems certainly useless to employ three functions, when two functions or even a single function would do just as well. The reason for this choice is that Boolean algebra permits logic nets to be designed very easily; their structure is clearer than that of nets based on other algebras, and, when realized physically, they are usually also more economical.

We shall therefore confine ourselves in our exposition to Boolean algebra. Our logic nets will thus consist of three types of elements, the behaviour of which is expressed by negation, conjunction and disjunction. These elements will be designated by the symbols shown in Fig. 8.1.

Let us note that the basic elements which model, for instance, negation, conjunction, disjunction, etc., cannot be subdivided, i.e. they cannot be built up of still simpler elements. That means, of course, that we are moving at the highest resolution level (see Sec. 2.3), i.e. that we are in the highest node of the resolution graph (see Sec. 2.4). We may,

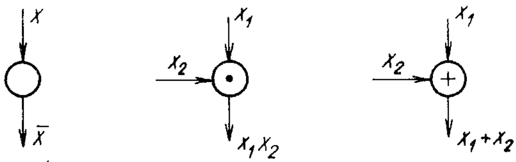

Fig. 8.1. Schematic symbols for the elements of logic nets

of course, gradually reduce the resolution level in various directions by considering several basic elements, included in the structure of the logic net, as a single element. This enables us to sketch, for every logic net, the complete resolution graph in detail from the lowest to the highest resolution level. This facility is one of the reasons why logic nets are such valuable aids to modelling.

8.4 BOOLEAN ALGEBRA

With the aid of elementary combinatorial analysis it is easy to ascertain that p logical independent variables can acquire 2^p different combinations of their values. It is possible to assign altogether 2^{2^p} different logical functions to these combinations. As already mentioned in the preceding section, any of these functions can be expressed by the triplet of simple functions which form the basis of Boolean algebra – negation, conjunction and disjunction.

The standard method of expressing logical functions in Boolean algebra is implied in the fundamental theorem of this algebra: *Any logical function F can always be expressed in the complete disjunctive normal form*

$$F = \sum_{i=0}^{2^p-1} F_i K_i \,, \tag{8.1}$$

where the symbol $\sum$ denotes the logical sum (disjunction), i the identifier of the independent variables, F_i are the values of the function F for identifier i, and K_i are the basic conjunctions corresponding to the identifier i. The basic conjunction is characterized by containing all the variables, either direct (in assertion) or negated. Negated are those variables, which in the given state have the value 0.

Let us now present a simple example with which we shall illustrate the relation (8.1). Let F be a logical function of three variables, presented in tabular form by its values F_i:

i	x_1	x_2	x_3	F_i	K_i
0	0	0	0	1	$\bar{x}_1\bar{x}_2\bar{x}_3$
1	0	0	1	0	$\bar{x}_1\bar{x}_2x_3$
2	0	1	0	1	$\bar{x}_1x_2\bar{x}_3$
3	0	1	1	1	$\bar{x}_1x_2x_3$
4	1	0	0	0	$x_1\bar{x}_2\bar{x}_3$
5	1	0	1	0	$x_1\bar{x}_2x_3$
6	1	1	0	1	$x_1x_2\bar{x}_3$
7	1	1	1	1	$x_1x_2x_3$

According to relation (8.1), this function can be expanded algebraically in the complete disjunctive normal form:

$$F = 1 \,.\, K_0 + 0 \,.\, K_1 + 1 \,.\, K_2 + 1 \,.\, K_3 + 0 \,.\, K_4 + 0 \,.\, K_5 + 1 \,.\, K_6 + 1 \,.\, K_7 \,.$$

Since in Boolean algebra we have $0 \,.\, x = 0$ and $1 \,.\, x = x$ (see page 169), the algebraic expansion of function F can be written in the simplified form:

$$F = K_0 + K_2 + K_3 + K_6 + K_7 \,.$$

Substituting the symbols K_i by the corresponding basic conjunctions already shown in the tabular representation of the function, we get:

$$F = \bar{x}_1\bar{x}_2\bar{x}_3 + \bar{x}_1x_2\bar{x}_3 + \bar{x}_1x_2x_3 + x_1x_2\bar{x}_3 + x_1x_2x_3 \,.$$

It will be noted that this is the sum of the basic conjunctions corresponding to those states of the independent variables for which the given function acquires the value 1.

The representation of a Boolean function in its complete disjunctive normal form can be successively simplified with the aid of various relations of Boolean algebra until we arrive at the so-called *minimal ex-*

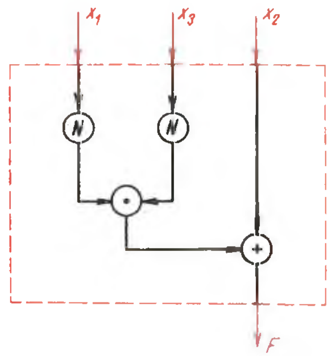

Fig. 8.2. Symbolic net modelling the Boolean function expressed by relation (8.2)

pansion of the corresponding function, which contains the least possible number of symbols. In the case presented above, the minimal algebraic expansion has the form:

$$F = x_2 + \bar{x}_3\bar{x}_1 \,. \tag{8.2}$$

The symbolic model of the logic net realizing this function is depicted in Fig. 8.2.

There are methods in the theory of logic nets which enable us to arrive by certain procedures at the minimal algebraic expansion of a given Boolean function. A description of these methods would, however, be beyond the scope of this book; we therefore only refer to the literary sources listed under [C7, C29].

In some instances we use Boolean functions that have no defined values for some states of the independent variables. In this case we speak of *indefinite Boolean functions.*

Let us now present, for the sake of completeness, a summary of the most important relations in Boolean algebra:

1. *Laws of the agressivity and neutrality of the values* 0 *and* 1

$$x \,.\, 0 = 0, \quad x \,.\, 1 = x$$

$$x + 0 = x, \quad x + 1 = 1$$

2. *Commutative laws*

$$x + y = y + x, \quad x \,.\, y = y \,.\, x$$

3. *Associative laws*

$$x(yz) = (xy)\,z, \quad x + (y + z) = (x + y) + z$$

4. *Distributive laws*

$$x(y + z) = xy + xz$$

$$x + (yz) = (x + y)\,(x + z)$$

5. *Law of double negation*

$$\bar{\bar{x}} = x$$

6. *Law of the excluded middle*

$$x + \bar{x} = 1, \quad x \,.\, \bar{x} = 0$$

7. *Laws of absorption*

$$x + x = x, \quad x \,.\, x = x$$

$$x(x + y) = x, \quad x + xy = x$$

8. *Laws of the absorption of negation*

$$x + \bar{x}y = x + y$$

$$\bar{x} + xy = \bar{x} + y$$

9. *De Morgan's laws* (Laws of the negation of sums and products)

$$\overline{x \,.\, y} = \bar{x} + \bar{y}$$

$$\overline{x + y} = \bar{x} \,.\, \bar{y}$$

Any of the laws of Boolean algebra can be verified in tabular form by successively applying negation, disjunction and conjunction to the

individual independent variables until we obtain a tabular representation of the corresponding expression. If we obtain the same representation for the right-hand and left-hand sides of the equation, this will be proof of its validity.

As an example let us present the verification of the second of De Morgan's laws by means of the following tables:

x	y	$x+y$	$\overline{x+y}$
0	0	0	1
0	1	1	0
1	0	1	0
1	1	1	0

x	y	$\bar{x}$	$\bar{y}$	$\bar{x}\,.\,\bar{y}$
0	0	1	1	1
0	1	1	0	0
1	0	0	1	0
1	1	0	0	0

It will be seen that the tabular representations of the expressions $\overline{x+y}$ and $\bar{x}\,.\,\bar{y}$ are the same. We have thus verified the validity of the given law.

It should be noted that any Boolean equation actually expresses the fact that two different algebraic equations model the same function. The logic nets modelling these expressions have the same behaviour but

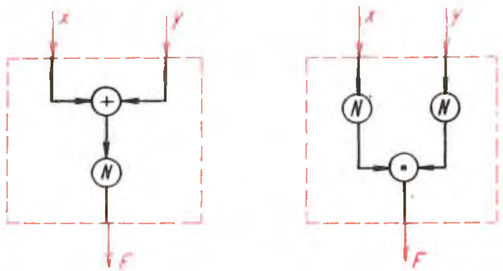

Fig. 8.3. Modelling of the same function F by different structures $(\overline{x+y} = \bar{x}\,.\,\bar{y})$

different structures. As an example we present in Fig. 8.3 the logic nets modelling the left-hand and right-hand side of the relation we have just verified.

Let us remark in conclusion that Boolean functions can also be expressed on the basis of De Morgan's laws in the so-called *complete conjunctive normal form*, i.e. as a conjunction of fundamental disjunctions. The general validity of our statements will not be prejudiced, however, if we confine ourselves to the form given by Eq. (8.1).

8.5 Models of Boolean Functions

The different methods of expressing Boolean functions, described in the preceding section (tabular, algebraic, etc.) may be regarded as their symbolic models. We are now going to describe further methods of modelling which are used in practice.

	0	1	2	3
0	0	1	2	3
1	4	5	6	7

$p = 3$

	0	1	2	3
0	0	1	2	3
1	4	5	6	7
2	8	9	10	11
3	12	13	14	15

$p = 4$

	0	1	2	3	4	5	6	7
0	0	1	2	3	4	5	6	7
1	8	9	10	11	12	13	14	15
2	16	17	18	19	20	21	22	23
3	24	25	26	27	28	29	30	31

$p = 5$

	0	1	2	3	4	5	6	7
0	0	1	2	3	4	5	6	7
1	8	9	10	11	12	13	14	15
2	16	17	18	19	20	21	22	23
3	24	25	26	27	28	29	30	31
4	32	33	34	35	36	37	38	39
5	40	41	42	43	44	45	46	47
6	48	49	50	51	52	53	54	55
7	56	57	58	59	60	61	62	63

$p = 6$

Fig. 8.4. Svoboda charts for $p = 3$ to 6 with indication of the corresponding identifiers

In place of the tabular form, a Boolean function can be expressed in an abridged form by means of a set of those identifiers of the independent variables, for which the corresponding function acquires the value 1. It is evident that a distinct fundamental conjunction corresponds uniquely to every identifier, and it is thus possible to pass on directly, for instance, to the complete disjunctive normal form according to the given set of identifiers.

A highly important method of expressing Boolean functions is the Svoboda chart (or map). In principle, *Svoboda's logic chart* is a square (for an even number of independent variables) or a rectangle (for an odd number of independent variables), regularly divided into 2^p small squares for p Boolean independent variables. A single identifier of the independent variables is assigned to every square, in the order in which the squares follow upon each other (from left to right and top to bottom).

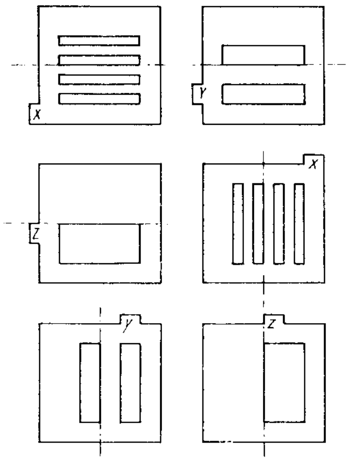

Fig. 8.5. Svoboda grids for 6 Boolean variables

Fig. 8.4 illustrates Svoboda charts for from 3 to 6 independent variables. The individual identifiers are entered in the corresponding spaces. Individual columns and rows have partial identifiers assigned to them, which we obtain providing that we divide all independent variables into two halves. We assume that, with Fig. 8.4 before us, it will be easy to visualize charts for a larger number of independent variables.

A Boolean function can be recorded in the chart by entering the functional value 1 in the corresponding spaces, the remaining spaces being left empty. For better clarity it is recommended to use, in place of the symbol 1, plain dots located in the middle of each square. The states of variables for which the given function is not defined (with indefinite functions) are usually marked by hatching the corresponding squares in the chart.

The individual Boolean variables can be modelled with advantage by

Svoboda charts with the aid of *grids* made, for instance, of cardboard. Such grids, intended for 6 variables, are shown in Fig. 8.5. Since there occur pairs of equal grids differing only by being rotated through 90° with respect to each other, small letters, e.g. $x, y, z, \ldots$, are used to denote one half of the variables, the corresponding capital letters, i.e. $X, Y, Z, \ldots$, being used for the second half. The pairs of grids $x-X$, $y-Y$, etc., thus differ only by their rotation through 90°.

If we place one of the grids on the chart (drawn to the same size as the grid), only those squares of the chart remain uncovered in which the corresponding variable acquires the value 1. If we turn any grid through an angle of 180° about the axes indicated in Fig. 8.5, we obtain a model of the negation of the corresponding variable.

If we place simultaneously several grids on the chart, we thereby model the conjunction of the corresponding variables, or of their negations. If several different groupings of grids are successively placed on the chart, the individual conjunctions will be bound together by disjunctions.

Svoboda charts and grids are excellent means for transforming the tabular representation of Boolean functions into a simple algebraic form. The procedure involving the use of these grids is very much simpler than that of proceeding via the complete disjunctive form and its simplification by the rules of Boolean algebra (since we always endeavour to obtain the algebraic expression of a given function in the simplest form possible). This is a typical example of a case when the use of a mathematical (algebraic) model (working with symbols) is less convenient than the use of a different model (working with grids and charts). Such instances are also encountered in other branches of mathematics (especially of applied mathematics) where a search for new, more efficient aids to modelling would be of greater value than the conservative adherence to classical methods.

A given Boolean function can be transformed from the chart into a simple algebraic form by placing suitably combined grids on the chart and writing out the corresponding conjunctions. On principle, no empty square in the chart must remain uncovered, whatever the combination of the grids. On the other hand, all squares occupied by a dot must be successively uncovered. This we endeavour to accomplish with the least possible number of grids.

As already shown in Sec. 8.4, every Boolean function represented by a certain algebraic expression can be modelled by a symbolic net with a single output, the net consisting of suitably coupled elements of

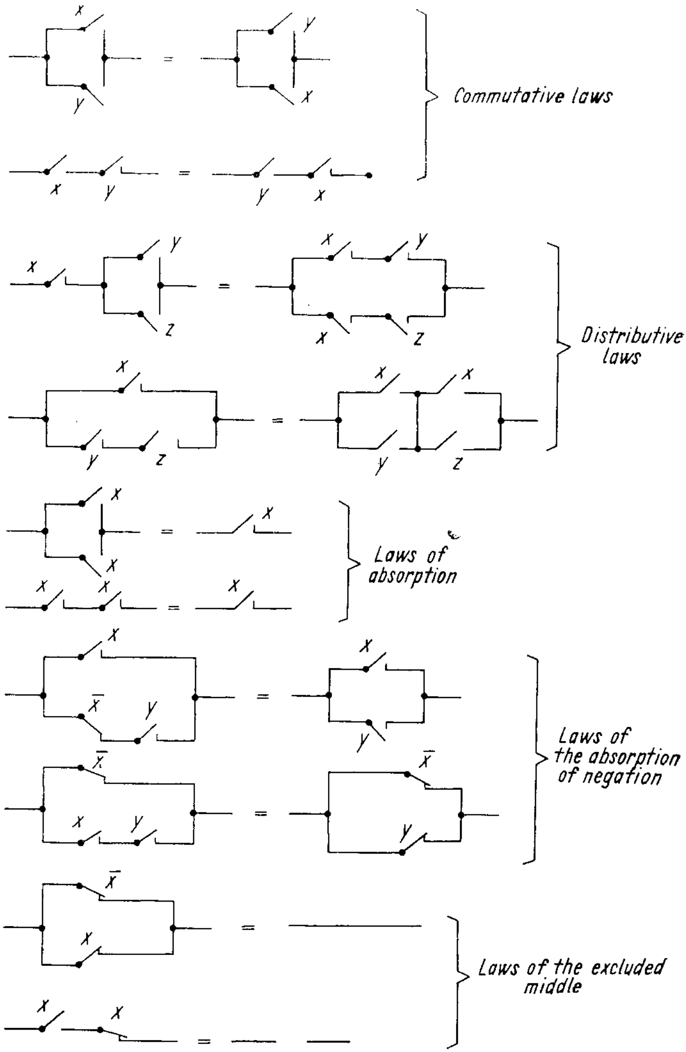

Fig. 8.6. Some of the laws of Boolean algebra expressed by switching circuits

negation, conjunction and disjunction. We are now going to show that every symbolically expressed logic net can be modelled by various physical systems. The main thing is to find physical systems capable of modelling the elements of negation, conjunction and disjunction. It is true that

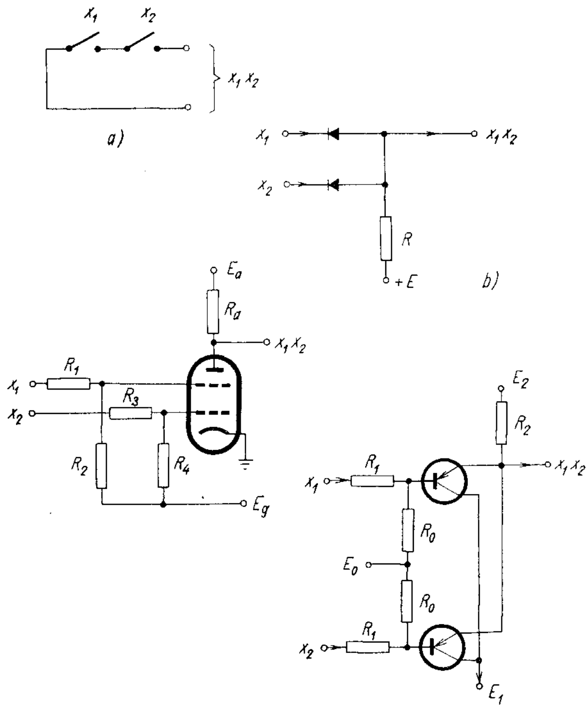

Fig. 8.7. Engineering models of conjunction

the best known of these are various electrical systems, but many other classes of systems are also in use (e.g. mechanical, pneumatic, hydraulic, etc.). Quite new and important systems capable of modelling elementary logical functions may be expected to turn up in the future (involving, for instance, the use of optical, chemical, biological or other principles). In this connection we should like to refer to an interesting paper listed under Ref. [B 39]. This paper contains a derivation of some general conditions a system must fulfil in order to be capable of modelling various logical functions of two independent variables.

The classical resources for the physical modelling of Boolean functions are *contact switching circuits*, no matter whether their contacts are operated manually or by electromagnets (relays).

The resting position and operating position of every contact must be clearly defined. If the contact is open in the resting position, it is called

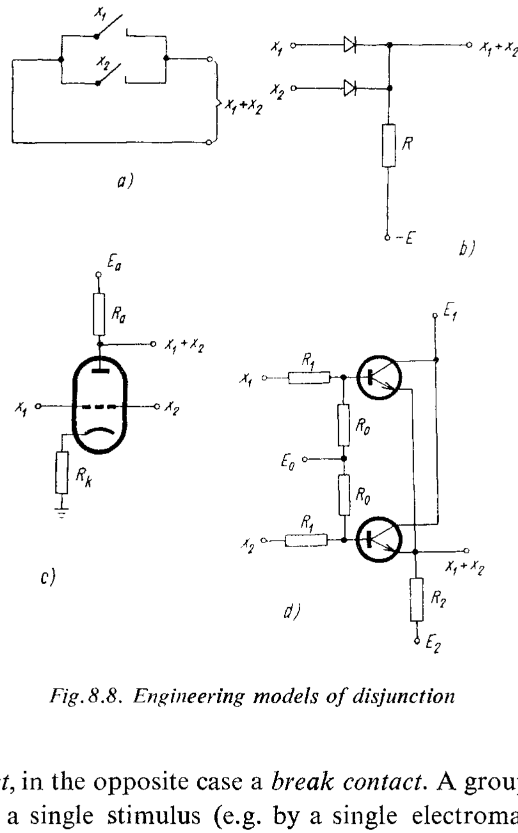

Fig. 8.8. Engineering models of disjunction

a *make contact*, in the opposite case a *break contact*. A group of contacts controlled by a single stimulus (e.g. by a single electromagnet) corresponds to a single Boolean independent variable. The make contact represents a variable in its normal form, whereas the break contact models its negation. Contacts connected in series model the conjunction of the corresponding variables or the conjunction of their negations. Contacts connected in parallel model their disjunction.

Fig. 8.6 illustrates, with the aid of contact switching circuits, some of

the laws of Boolean algebra presented in Sec. 8.4. All the contacts are depicted in their resting positions.

As already mentioned, the fundamental functions of Boolean algebra can be modelled also in many different ways. However, we cannot afford to go in for a broader discussion of this problem. We therefore present in Figs. 8.7 to 8.9 for purposes of illustration the schematic represensation of at least some of the best known electrical models.

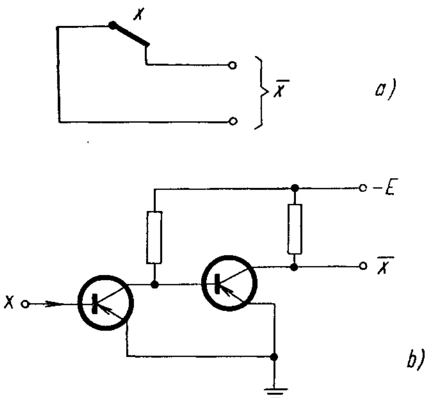

Fig. 8.9. Engineering models of negation

Let us now present various methods of modelling a simple Boolean function. As an example we take the function F, expressed by the following table:

i_2	i_1	i	X	y	x	F
0	0	0	0	0	0	0
0	1	1	0	0	1	1
0	2	2	0	1	0	0
0	3	3	0	1	1	0
1	0	4	1	0	0	1
1	1	5	1	0	1	1
1	2	6	1	1	0	1
1	3	7	1	1	1	0

The notation of the variables has been chosen so as to correspond to the method used in the charts and grids. The partial identifiers i_1 and i_2 have been introduced for the same reason. The identifier i_1 (the number

determining the column in the chart) expresses in decimal notation the binary numbers corresponding to the variables x and y. Similarly, the identifier i_2 (the number giving the row in the chart) expresses in decimal notation the numbers accompanying the variable X. Since in this case we are concerned with a single variable, we may write directly $i_2 = X$.

	0	1	2	3
0		•		
1	•	•	•	

Fig. 8.10. Chart model of function $F = X\bar{x} + \bar{y}x$

Let us first put down the complete disjunctive normal form of the corresponding function:

$$F = \bar{X}\bar{y}x + X\bar{y}\bar{x} + X\bar{y}x + Xy\bar{x}\,.$$

By successive rearrangements we would arrive at the minimal algebraic expansion:

$$F = X\bar{x} + \bar{y}x\,.$$

The function F expressed by the set of identifiers assumes the following form:

$$F = \{1, 4, 5, 6\}\,.$$

The chart model of function F is shown in Fig. 8.10. Fig. 8.11 presents the symbolic net which models its minimal algebraic expansion, and Fig. 8.12 illustrates the corresponding contact switching circuit.

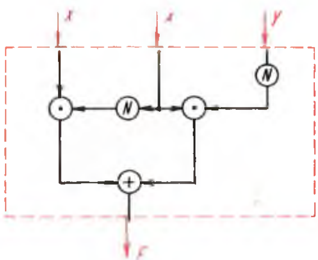

Fig. 8.11. Symbolic net modelling the function $F = X\bar{x} + \bar{y}x$

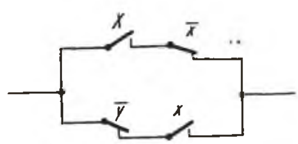

Fig. 8.12. Contact switching circuit modelling the function $F = X\bar{x} + \bar{y}x$

8.6 Combinatorial Nets

We have dealt so far only with the model of a single Boolean function. We know that a Boolean function can be modelled by a logic net with a single partial output. As to logic nets with several partial outputs, they actually model several functions.

Now let us see what the synthesis of logic nets consists of. We already know from Chapter 1, that the synthesis of a system consists of finding a structure (using sets of elements of a given type) which would realize the given behaviour and, if necessary, also meet some secondary requirements.

The elements used in logic nets to produce their structure are, as a rule, conjunction, disjunction and negation, the behaviour being usually given in the form of a table. One part of the table contains the values of the partial stimuli, its second part the values of the partial responses.

Partial stimuli are regarded as Boolean independent variables, partial responses as Boolean functions. The principal task of the synthesis is then to find algebraic models of the corresponding function, because these already express the structure of the corresponding logic net.

Every Boolean function has an infinite number of algebraic models. When we want to realize logic nets (and usually also at other times), we try to find the simplest possible algebraic forms, i.e. we attempt to reduce the number of elementary functions in the corresponding algebraic expressions to a minimum.

Svoboda charts and grids are suitable means for the conversion of Boolean functions from the tabular form to the minimal algebraic expansion. We therefore prefer to model Boolean functions first by charts – it is then easy to transform them directly into the minimal algebraic expansion. Sometimes, should this be possible, we present the problem directly in the form of a chart, so that the tabular representation need not be used at all. We must remember, of course, that a separate chart is required for every partial output.

Let us note that both the table and the set of charts are actually symbolic models of the behaviour of a distinct combinatorial logic net. We are here concerned with models that are independent of (i.e. invariant to) the structure which produces the corresponding behaviour. This leads

to the important conclusion that, when investigating combinatorial logic nets from the viewpoint of a "black box", it is possible to find a model of the corresponding net in the form of a table or of a Svoboda chart, but not an algebraic model. If necessary, however, it will be possible to produce a homomorphic algebraic model.

8.7 An Example of Synthesis

To make the foregoing exposition easier to understand, we shall now present the synthesis of a simple combinatorial logic net with four partial inputs and four partial outputs, whose behaviour is given by the following table:

i_2	i_1	Y	X	y	x	f_1	f_2	f_3	f_4
0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	1	0	0	0	1
0	3	0	0	1	1	0	0	1	0
0	2	0	0	1	0	0	0	1	1
1	2	0	1	1	0	0	1	0	0
3	2	1	1	1	0	0	1	0	1
3	3	1	1	1	1	0	1	1	0
1	3	0	1	1	1	0	1	1	1
1	1	0	1	0	1	1	0	0	0
3	1	1	1	0	1	1	0	0	1

Let us note that in this case the actual variety at the input (ten defined stimuli) is smaller than the full variety at the input (16 possible stimuli). The Boolean functions f_1 to f_4, whose chart models are shown in Fig. 8.13, are therefore indefinite functions. The squares for which the functions are not defined are marked in the charts by hatching. These squares may be imagined, as required, to be either empty or to contain a dot. This will not affect the result in any way whatsoever, since the stimuli corresponding to these squares have no meaning in the given system.

By applying the grids to the chart models, we can easily arrive at the minimal algebraic expansions of the individual functions:

$$f_1 = X\bar{y}$$
$$f_2 = Xy$$
$$f_3 = \bar{X}y + yx$$
$$f_4 = \bar{Y}Xyx + \bar{X}y\bar{x} + \bar{X}\bar{y}x + Y\bar{y} + Y\bar{x}\,.$$

We recommend that readers, to whom the problem of logic nets is new, ascertain for themselves with the aid of suitable grids that the algebraic

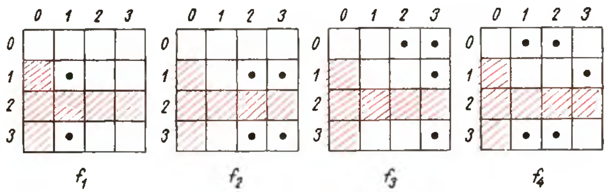

Fig. 8.13. Chart models of the functions used in the example of synthesis

expansions presented above really correspond to the chart models of Fig. 8.13. From the didactic point of view it would also be useful if the reader attempted to derive the minimal expansions of the functions f_1 to f_4 from their complete disjunctive normal forms with the help of the rules of Boolean algebra.*)

The process of ascertaining the minimal algebraic expansions of individual Boolean functions is the most difficult part of the synthesis of combinatorial logic nets. It is possible to achieve a further simplification of some functions by a suitable factorization of symbols on the basis of the distributive law. In our case this can be done with functions f_3 and f_4:

$$f_3 = y(\bar{X} + x)$$
$$f_4 = y(\bar{Y}Xx + \bar{X}\bar{x}) + \bar{y}(\bar{X}x + Y) + Y\bar{x}\,.$$

Based on the algebraic expansions rewritten in this way we can already sketch the symbolic structure of the logic net to be designed. This is

*) The reader should remember, however, that he may add to the normal form (only, of course, if this would be of any use in the given case) even those fundamental conjunctions, for which the value of the corresponding function is not defined.

presented in Fig. 8.14. We should add that in engineering applications, where we try to attain maximum economy, this phase of synthesis (the conversion from the algebraic form to the structure of the net) is often

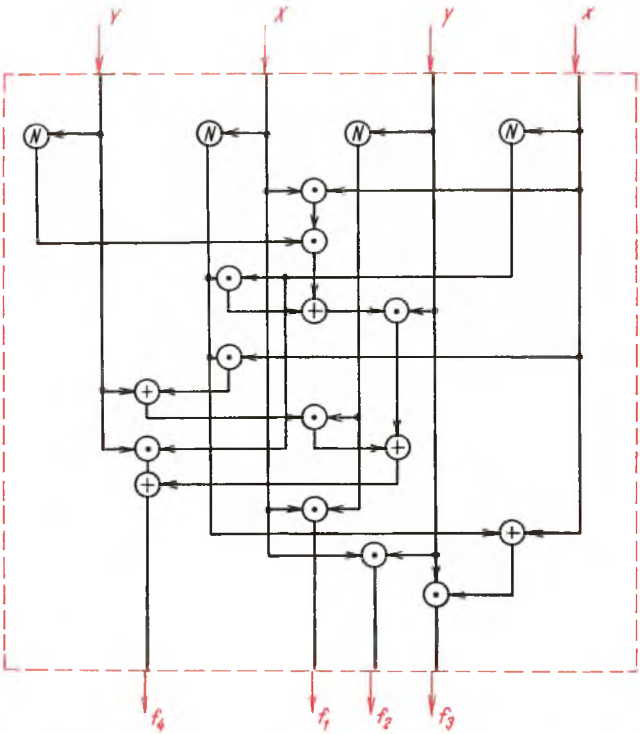

Fig. 8.14. Symbolic model of the proposed combinatorial logic net

rather difficult. This is because the physical peculiarities of various elements enable us sometimes (e.g. in contact switching circuits) to employ special circuit techniques which, although they cannot by expressed directly in algebraic form (e.g. bridge circuits), are nevertheless highly economical.

Let us note that the logic net shown in Fig. 8.14 can already be easily modelled by physical means. It will be sufficient to produce models of

conjuction, disjunction and negation and to interconnect them according to Fig. 8.14.

8.8 SEQUENTIAL NETS

In sequential logic nets the response depends not only on the instantaneous stimulus, but in general on the whole sequence of prior stimuli. This is due to the fact that sequential nets contain, in addition to logic elements (models of conjunction, disjunction and negation) also *storage elements.*

The elementary storage device is characterized by being capable of presenting, at the instant t_2, information on a stimulus received at the instant t_1, where $\Delta t = t_2 - t_1 > 0$. In this respect we distinguish elements with a fixed time interval Δt *(delay elements)* from elements where the time interval Δt depends on the momentary exigency *(permanent storage elements).*

Storage elements of the most diverse types are available [C 23, C 29]. For our discussion we shall selecto nly one of the possible types, whose function is easily intelligible.

Let us assume that the storage element under consideration has two partial inputs denoted by u and v respectively, and one partial output denoted by z. Only three different stimuli are accessible at the input, so that the input variety is not full. The stimuli produce the following effects:

1. The stimulus $u = v = 0$ does not alter the prior response z.

2. The stimulus $u = 1$ and $v = 0$ always produces the response $z = 1$.

3. The stimulus $u = 0$ and $v = 1$ always produces the response $z = 0$.

The stimulus $u = 1$ and $v = 1$ is inadmissible.

If the symbol z denotes the response before a given stimulus has taken effect, and the symbol z' the response after this stimulus has become operative, the function of the storage element under consideration can be described by the following Boolean table:

i	u	v	z	z'
0	0	0	0	0
0	0	0	1	1
1	0	1	0	0
1	0	1	1	0
2	1	0	0	1
2	1	0	1	1

This storage element will be marked in our diagrams by a rectangle with two inputs and one output, with the symbol ***P*** inscribed.

Let us assume that our sequential logic nets will thus be built up of elements of four types: conjunction, disjunction, negation, and the storage element ***P***. With this assumption in mind we can already consider the general block diagram of a sequential logic net as illustrated in Fig. 8.15.

The basis of this sequential logic net is a combinatorial logic net which,

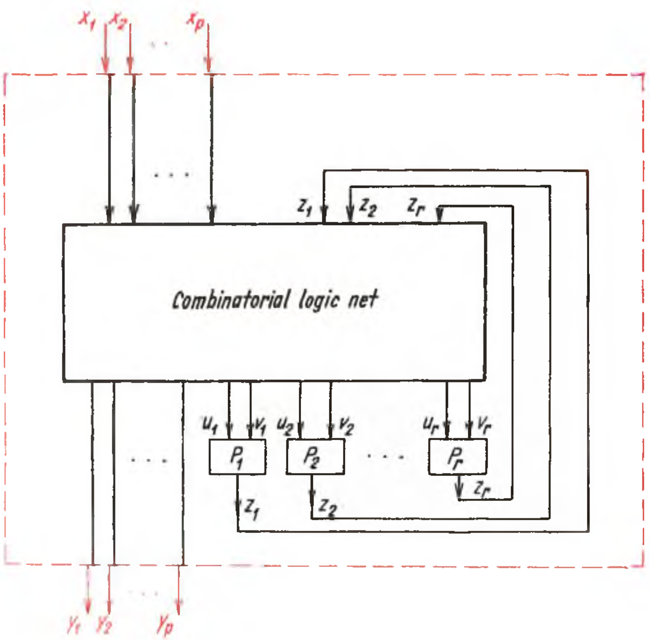

Fig. 8.15. General block diagram of sequential logic net

in addition to the outputs $y_1, y_2, \ldots, y_q$ has the further (internal) outputs $u_1, u_2, \ldots, u_r$, $v_1, v_2, \ldots, v_r$ entering the storage elements P_1, $P_2, \ldots, P_r$. The outputs of these storage elements, $z_1, z_2, \ldots, z_r$, are coupled to the input of our combinatorial net. They thus form further (internal) inputs which, together with the inputs $x_1, x_2, \ldots, x_p$ take part in producing the responses at the outputs $y_1, y_2, \ldots, y_q$.

Let us note that to an external observer who perceives only the inputs $x_1, x_2, \ldots, x_p$ and the outputs $y_1, y_2, \ldots, y_q$, the behaviour of the sequential logic net may appear random. If, however, he also includes the internal inputs $z_1, z_2, \ldots, z_r$ in his observations, he will find that the behaviour of the system is determinate.

8.9 THE SYNTHESIS OF SEQUENTIAL NETS

The behaviour of a sequential net may be propounded by various means (verbally, by a time diagram, etc.). In its synthesis we are mainly concerned with transforming the data given into a form which might serve as a suitable basis for synthesis. In this respect we consider the behaviour graph (Chapter 2) to be the most suitable expedient.

With the aid of the behaviour graph we must first fix the number of storage elements required, and then determine suitable states of the internal variables $z_1, z_2, \ldots, z_r$ (see Fig. 8.15) for the individual nodes of the graph. This is the fundamental and also the most difficult part of the synthesis of sequential nets. The rest then actually consists in the synthesis of a combinatorial net with the inputs $x_1, x_2, \ldots, x_p$, $z_1, z_2, \ldots, z_r$ and the outputs $y_1, y_2, \ldots, y_q$, $u_1, u_2, \ldots, u_q$, $v_1, v_2, \ldots, v_r$.

If a given sequential logic net is to be modelled physically, we must start from the fact that the reaction times (see Sec. 4.6) of the individual storage elements will differ from each other (unless they are synchronized in some manner). It is then desirable to choose the states of the internal variables $z_1, z_2, \ldots, z_r$ so that two adjacent nodes in the behaviour graph always differ by the value of a single internal variable. If, moreover, we want the realization of the logic net to be as economical as possible, we are confronted with a very difficult problem that has not by any means yet been solved in all its aspects.

8.10 THE LOGIC NET AS A "BLACK BOX"

When experimenting with a logic net as a "black box", we may encounter two cases:

1. The behaviour is evidently determinate.
2. Initially, the behaviour appears completely random; after continued experimentation it is found to be determinate but dependent upon the order of the stimuli.

In the first case it is relatively easy to determine the behaviour in the form of a table or with the aid of a suitable set of charts. We cannot ascertain the real structure of the combinatorial net involved; we can only propound various hypotheses based on a synthesis performed with regard to the ascertained behaviour. A particular hypothesis can be verified, of course, only by "looking" into the "black box", i. e. (in biological systems, for instance) by a physiological or anatomical investigation.

In the second case, an analysis of behaviour will be far more difficult. The duration of the experiment required depends, on the one hand, on the complexity of the net (the capacity of the internal store and the number of partial inputs and outputs), on the other hand on the skill and experience of the experimentalist. The result of the experiment is a behaviour graph. From this we can judge whether the structure of our "black box" corresponds to the general structure of the sequential logic net illustrated in Fig. 8.15. It is also possible to determine indirectly the smallest number of combinations of the internal variables sufficient to produce the corresponding behaviour. From this we can obtain an estimate of the minimum number of storage elements. However, we cannot ascertain their actual number, since we do not know the method of internal coding. Neither can we determine the structure of the combinatorial logic net involved which, according to Fig. 8.15, is the fundamental element in the structure of sequential logic nets. Various hypotheses can be made in this respect by means of a synthesis based on the behaviour graph. They can be definitely verified only by "opening" the "black box".

In this context we should mention yet another obstacle the experimentalist is likely to encounter when investigating a "black box". The

problem is that the typically sequential behaviour of a system may manifest itself for some time as purely combinatorial, and alter this aspect only after a suitable sequence of stimuli (when attaining a suitable state of the store).

A very simple example of the aforementioned possibility is the well-known conditioned reflex. This will be shown in the following section, where we are going to treat the modelling of a conditioned reflex by a sequential logic net.

8.11 The Model of a Conditioned Reflex

When designing a sequential logic net which is intended to model the behaviour of a given psychological or biological system, the requisite procedure consists of several characteristic phases:

1. A description of the behaviour of the system under observation must first be put together on the basis of experiments. The precision of the model depends on the accuracy and completeness of this description.
2. On the basis of the description it will be possible to delimit the set of stimuli and the set of responses.
3. The described relations between stimuli and responses are used to set up a behaviour graph. The states of the internal variables (storage elements), which differ from each other, are then denoted by general symbols written down adjacent to the individual nodes.
4. Concrete meanings are suitably assigned to the states of the internal variables (the storage elements).
5. A table is set up containing the behaviour of the combinatorial logic net which forms the basis of the sequential net (see Fig. 8.15).
6. The table is transformed into algebraic form.
7. According to the algebraic expressions a symbolic model is sketched of the proposed sequential net.
8. The resulting design is analysed in order to ascertain whether its behaviour is identical with that of the original.

The procedure outlined above will now be illustrated by a simple example. For this purpose we have selected the behaviour of a biological system observed while a simple conditioned reflex is being set up. This example is well known and is, on the whole, quite simple so that the

problem of modelling by sequential logic nets can be very clearly illustrated by it.

As already mentioned, modelling must be based on a description of the behaviour observed in the course of experiments. The creation of a conditioned reflex might be described, for instance, as follows: In the biological system under observation (e.g. a dog) it was found that a

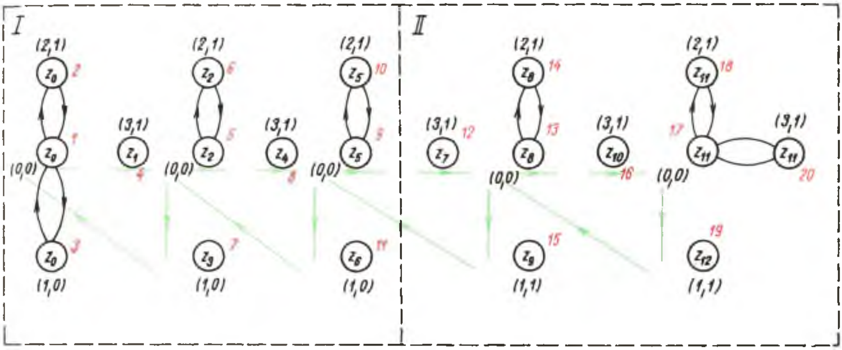

Fig. 8.16. Behaviour graph expressing the properties of a conditioned reflex

certain stimulus H (the main stimulus, e.g. the presentation of food) always evoked a response R (e.g. salivation) watched by the observer. The stimulus V (secondary stimulus, e.g. the sound of a bell) does not provoke the response R. When both stimuli are simultaneously presented to the system, the response R will be observed. A peculiar situation arises when both stimuli are simultaneously presented to the system a-times in succession. The response R will then be once observed even when only the stimulus V is applied to the system. If both stimuli are applied $(a + b)$-times, then the response R will appear either at the $(b + 1)$-st repetition of stimulus V (if $b \leq k$, where k is a fixed number), or at the $(k + 1)$-st repetition of stimulus V (if $b > k$).

As appears from the foregoing description, the set of stimuli in this case consists only of the stimuli H (main) and V (secondary), whereas the set of responses contains only a single element, R.

In order to be able to set up a behaviour graph let us choose, for instance, $a = 3$ and $k = 1$. The behaviour graph corresponding to the

given description is shown in Fig. 8.16. The pair of numbers assigned to every node defines the stimulus-reaction pair (in this order). The stimuli are denoted in abridged form by their identifiers i in accordance with the following table:

H	V	i
0	0	0
0	1	1
1	0	2
1	1	3

The states of the internal variables (the storage elements) are denoted in general form by the symbols $\boldsymbol{Z}_0$ to $\boldsymbol{Z}_{12}$ inscribed in the circles which depict the individual nodes of the graph. They differ from each other only when this is unavoidable in order to obtain the desired behaviour.

Now let us assign concrete meanings to the individual states of the internal variables. If we want to realize the proposed model physically, we must add the requirement that two adjoining states $\boldsymbol{Z}_i$ differ by the value of only a single variable (by the state of a single storage element). This condition can be satisfied by five internal variables, $\mathbf{z}_1$ to $\mathbf{z}_5$, assigned, for instance, as follows:

$\boldsymbol{Z}_i$

i	z_1	z_2	z_3	z_4	z_5
0	0	0	0	0	0
1	0	0	0	1	0
2	0	0	0	1	1
3	0	0	0	0	1
4	0	1	0	1	1
5	0	1	1	1	1
6	0	0	1	1	1
7	0	1	1	0	1
8	0	1	1	0	0
9	0	1	1	1	0
10	0	1	0	0	0
11	1	1	0	0	0
12	1	1	1	0	0

Having determined the values of $\boldsymbol{Z}_i$, the graph is fully defined and we can proceed to set up a table of the behaviour of our combinatorial net. However, let us first dwell for another moment on the behaviour graph proper.

From the behaviour graph we can obtain any sequence out of the infinite set of all possible sequences of stimuli. For every sequence of stimuli we can easily find the resulting response. The study of the structure of the behaviour graph is, however, very instructive in other respects

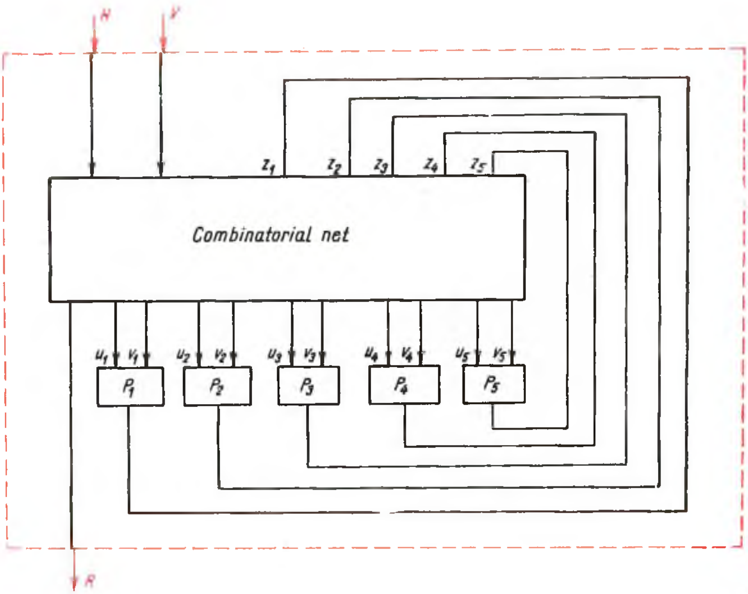

Fig. 8.17. Block diagram of a model of the conditioned reflex illustrated by the behaviour graph in Fig. 8.16

also. Let us note, for instance, that an experimentalist who chooses an unsuitable sequence of stimuli can move for any length of time in the left-hand part of the graph (marked I) only. Such an experimentalist would necessarily regard the behaviour of the system as purely combinatorial and would never discover the conditioned reflex. We should remark that, in biological systems, the left-hand as well as the right-hand part of the graph are frequently very much more extensive (the numbers a and k are larger) than in our case.

Table 8.1. Table of Conditioned Reflex

i_1	i_2	Z H	Y V	X z_1	t z_2	z z_3	y z_4	x z_5	R	u_1	u_2	u_3	u_4	u_5	v_1	v_2	v_3	v_4	v_5	Node or Transition	State
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	—	—	—	—	—	1	*e*
4	0	1	0	0	0	0	0	0	1	0	0	0	0	0	—	—	—	—	—	2	*e*
2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	—	—	—	—	—	3	*e*
6	0	1	1	0	0	0	0	0	—	0	1	0	0	0	—	0	—	—	—	1→ 4	*n*
6	2	1	1	0	0	0	1	0	1	0	—	0	0	0	—	0	—	—	—	4	*e*
0	2	0	0	0	0	0	1	0	—	1	—	0	0	0	0	0	—	—	—	4→ 5	*n*
0	3	0	0	0	0	0	1	1	0	—	—	0	0	0	0	0	—	—	—	5	*e*
4	3	1	0	0	0	0	1	1	1	—	—	0	0	0	0	0	—	—	—	6	*e*
2	3	0	1	0	0	0	1	1	—	—	0	0	0	0	0	1	—	—	—	5→ 7	*n*
2	1	0	1	0	0	0	0	1	0	—	0	0	0	0	0	—	—	—	—	7	*e*
0	1	0	0	0	0	0	0	1	—	0	0	0	0	0	1	—	—	—	—	7→ 1	*n*
6	3	1	1	0	0	0	1	1	—	—	—	0	1	0	0	0	—	0	—	5→ 8	*n*
6	11	1	1	0	1	0	1	1	1	—	—	0	—	0	0	0	—	0	—	8	*e*
0	11	0	0	0	1	0	1	1	—	—	—	1	—	0	0	0	0	0	—	8→ 9	*n*
0	15	0	0	0	1	1	1	1	0	—	—	—	—	0	0	0	0	0	—	9	*e*
4	15	1	0	0	1	1	1	1	1	—	—	—	—	0	0	0	0	0	—	10	*e*
2	15	0	1	0	1	1	1	1	—	—	—	—	0	0	0	0	0	1	—	9→11	*e*
2	7	0	1	0	0	1	1	1	0	—	—	—	0	0	0	0	0	—	—	11	*e*
0	7	0	0	0	0	1	1	1	—	—	—	0	0	0	0	0	1	—	—	11→ 5	*n*
6	15	1	1	0	1	1	1	1	—	—	0	—	—	0	0	1	0	0	—	9→12	*n*
6	13	1	1	0	1	1	0	1	1	—	0	—	—	0	0	—	0	0	—	12	*e*
0	13	0	0	0	1	1	0	1	—	0	0	—	—	0	1	—	0	0	—	12→13	*n*
0	12	0	0	0	1	1	0	0	0	0	0	—	—	0	—	—	0	0	—	13	*e*
4	12	1	0	0	1	1	0	0	1	0	0	—	—	0	—	—	0	0	—	14	*e*
2	12	0	1	0	1	1	0	0	—	0	1	—	—	0	—	0	0	0	—	13→15	*n*
2	14	0	1	0	1	1	1	0	1	0	—	—	—	0	—	0	0	0	—	15	*e*
0	14	0	0	0	1	1	1	0	—	1	—	—	—	0	0	0	0	0	—	15→ 9	*n*
6	12	1	1	0	1	1	0	0	—	0	0	0	—	0	—	—	1	0	—	13→16	*n*
6	8	1	1	0	1	0	0	0	1	0	0	0	—	0	—	—	—	0	—	16	*e*
0	8	0	0	0	1	0	0	0	—	0	0	0	—	1	—	—	—	0	0	16→17	*n*
1	8	0	0	1	1	0	0	0	0	0	0	0	—	—	—	—	—	0	0	17	*e*
5	8	1	0	1	1	0	0	0	1	0	0	0	—	—	—	—	—	0	0	18	*e*
3	8	0	1	1	1	0	0	0	—	0	0	1	—	—	—	—	—	0	0	17→19	*n*
3	12	0	1	1	1	1	0	0	1	0	0	—	—	—	—	—	—	0	0	19	*e*
1	12	0	0	1	1	1	0	0	—	0	0	—	—	0	—	—	—	0	1	19→13	*n*
7	8	1	1	1	1	0	0	0	1	0	0	—	—	—	—	—	—	0	0	20	*e*

The block diagram of a model of the conditioned reflex corresponding to the behaviour graph of Fig. 8.16 is presented in Fig. 8.17. Let us now set up a table of the behaviour of the combinatorial logic net, which is uniquely determined by the fully defined behaviour graph. When making up the table, we must pass through all the nodes and over all the connecting lines of the graph in succession. Special attention must be devoted to the transitions where the internal state $\boldsymbol{Z}_i$ undergoes a change. In these cases we always first encounter a non-equilibrial state which, however, immediately turns into a state of equilibrium (and this is how it must be described in the table). The rows in the table which correspond to equilibrial states are marked by the symbol e, those corresponding to non-equilibrial states by the symbol n. Indefinite values of functions are denoted by the symbol – . Under these assumptions we obtain the Table 8.1.

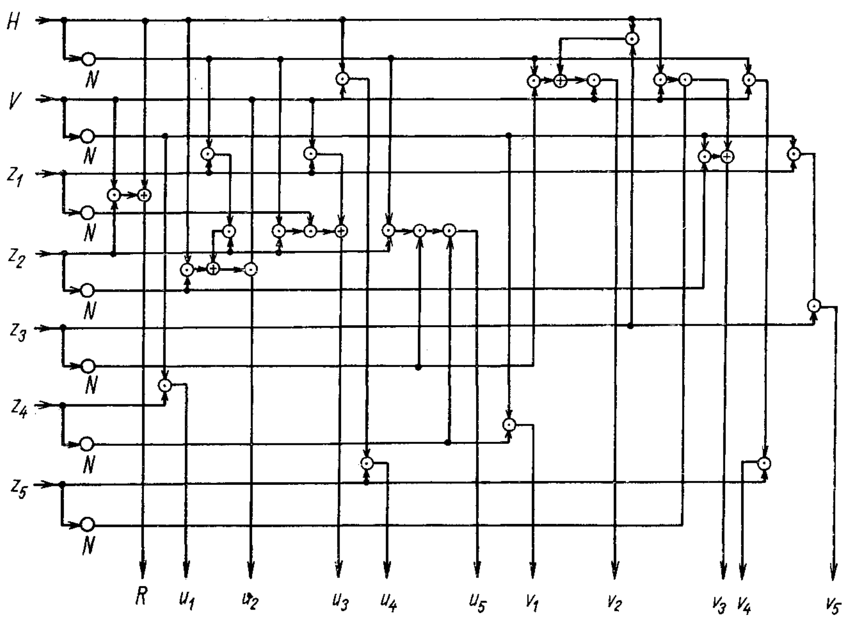

Fig. 8.18. Detailed diagram of the model of the conditioned reflex according to the behaviour graph in Fig. 8.16

The values of logic independent variables are designated in the table in two ways. The first type of designation corresponds to the symbols used in Fig. 8.17, the second is in agreement with the symbols used in the charts and grids, which can be utilized with advantage to facilitate the conversion of functions expressed in tabular form into a simple algebraic form. The table also comprises the pairs of the identifiers i_1 and i_2, customary in charts.

Owing to our having identified the individual rows of the table with the corresponding nodes or transitions between the nodes by means of the ordinal numbers of the nodes, the table can be easily compared with the behaviour graph and with the table of the values of $\mathbf{Z}_i$. We therefore assume that the table needs no further commentary.

We can now (for instance with the aid of charts and grids) set up the corresponding algebraic expressions for the individual functions, i.e. $R, u_1, \ldots, u_5, v_1, \ldots, v_5$. We recommed that readers who are not versed in the synthesis of logic nets write down, on their own, the corresponding functions in the charts (each chart having 8 rows and 16 columns) and find their simplest possible algebraic representation by means of grids. If they proceed in the correct manner, they should arrive at the following expressions:

$$
\begin{aligned}
R &= Z + Yt = H + Vz_2\\
u_1 &= \bar{Y}y = \bar{V}z_4\\
u_2 &= Y(Z\bar{t} + \bar{Z}\bar{X}t) = V(H\bar{z}_2 + \bar{H}\bar{z}_1 z_2)\\
u_3 &= YX + \bar{Z}ty = Vz_1 + \bar{H}z_2 z_4\\
u_4 &= ZYx = HVz_5\\
u_5 &= \bar{Z}t\bar{z}\bar{y} = \bar{H}z_2\bar{z}_3\bar{z}_4\\
v_1 &= \bar{Y}\bar{y} = \bar{V}\bar{z}_4\\
v_2 &= Y(\bar{Z}\bar{z} + Zz) = V(\bar{H}\bar{z}_3 + Hz_3)\\
v_3 &= \bar{Y}\bar{t} + ZY\bar{x} = \bar{V}\bar{z}_2 + HV\bar{z}_5\\
v_4 &= \bar{Z}Yx = \bar{H}Vz_5\\
v_5 &= \bar{Y}Xz = \bar{V}z_1 z_3
\end{aligned}
$$

Using the algebraic expressions given above, it is easy to sketch, in a symbolic notation (see Fig. 8.18), the combinatorial logic net shown

in the block diagram of Fig. 8.17 as a box. In this manner we get a symbolic model of the conditioned reflex which satisfies the behaviour graph of Fig. 8.16. It now remains to perform an analysis of this model to make sure that no error has occurred in its design.

If desired, the model can be physically realized assuming, of course, that we possess elements which model conjunction, disjunction and negation.

Part Two

BIOLOGICAL SYSTEMS AS OBJECTS OF MODELLING

CHAPTER 9

CYBERNETIC SYSTEMS IN BIOLOGY

In this chapter we shall first try to delimit the spheres common to cybernetics and biology. At the same time we want to present, in an acceptable manner, a basic orientation in the biological sciences to those readers, who are not yet acquainted with this field. Of course, we are aware of the fact that, owing to this approach, some passages will be quite without interest to workers in the biological sciences.

Our way of explaining the relevant problems is intended primarily for those working in the engineering sciences, since they are becoming increasingly interested in biological systems. This is because some biological systems seem to offer outstanding advantages as patterns for engineering purposes. It may be expected that the thorough understanding of these systems and their modelling will introduce entirely new principles into engineering. The most promising, as far as their contribution to engineering is concerned, are those systems which might be called biocybernetic. This term is intended to mean cybernetic systems defined in animate matter.

A discussion of the nervous system, which can be considered as the most complicated biocybernetic system in man, is deferred to Chapter 10.

9.1 BIOLOGY

Biology in the wider sense of the word is usually understood to mean the science dealing with the study of the most diverse properties of living matter. This conception would be quite clear, provided we could base it on a definition of living matter as such. However, such a definition does not exist – or at least not a fully satisfactory one. The main difficulty consists in that living matter is made up of the same chemical

elements as inanimate matter, and that the same physical and chemical laws are applicable to it as to inanimate matter, e.g. the law of the conservation of energy, the laws of chemical bonding, etc. The difference evidently consists only in the complexity of the chemical organization and reveals itself by the fact that matter, complexly organized in a certain manner, shows some qualitatively new properties.

When deciding whether a given system is living, we can base our judgement either on the behaviour of this system, or on its structure. The conclusions derived from its behaviour should be in agreement with the results arrived at on the basis of its structure.

Judged according to its behaviour, a given system is considered to be live only if its behaviour exhibits some specific properties. These are chiefly:

1. *Metabolism, i.e. the exchange of matter and energy* between the system and its environment, which ensures the preservation of the fundamental properties of the system under varying conditions. Metabolism, of course, changes with time – a process termed "ageing of the system". At a certain degree of ageing we arrive at a state when metabolism is no longer capable of maintaining the fundamental properties of the system. Finally, the structure disintegrates, the system losing all properties of living matter. In such a case we speak of the natural death of the living system. In metabolism we distinguish between two opposite processes:

a) *assimilation* or *anabolism* – the intake of matter and energy from the environment and their transformation into substances proper to the system,

b) *dissimilation* or *catabolism* – breaking down of substances in the system, connected with the release of energy.

2. *Excitability* combined with adaptability, i.e. the capacity to react actively upon environmental stimuli, i.e. in a manner differing from that which, seen from outside, would correspond to common physical and chemical laws. The energy required for this activity is derived from internal biochemical sources which are constantly supplemented from the environment with the aid of metabolism.

3. *Reproducibility*, the individual aspects of which are *growth*, *differentiation*, *self-organization*, and *reproduction*. Growth can take place

only under the assumption that the matter obtained from the environment by metabolism partially accumulates in the system for a certain time (a considerably long one, as a rule). However, this accumulation of matter manifests itself not only by an increase in the mass of individual elements of the system, but also by changes in their structure. Such changes in the structure of individual elements may differ from each other, so that the elements become gradually differentiated. We must, however, distinguish changes of two kinds:

a) particles of matter obtained from the environment are incorporated in the structure of the element without disturbing its integrity,
b) a certain part separates from the element and forms the germ of a new element, equipped with properties similar to those of the original element.

In the first case we speak of the capacity for *self-organization* in living matter, in the second case of *reproduction*. Let us note that in both cases a change takes place in the supersystem (see Sec. 2.12).

From the point of view of structure, the basis of living matter is considered to consist of some specific *high-molecular chemical compounds*, especially *proteins* and *nucleic acids*, sometimes also of their complexes *(nucleo-proteins)*. This view is based on the experience that all systems in nature, in which metabolism, excitability, reproducibility etc. can be observed, always contain a considerable amount of some of the substances mentioned.

The definition of living systems based on their structure thus actually relies on their definition based on behaviour. It is not quite clear, however, which complex compounds of these substances and what conditions are necessary for the system to live. The situation is made more difficult particularly by some microscopic and submicroscopic systems (*viruses*, *bacteriophages*, etc.), which are made up of simple nucleoproteins. When isolated from living matter, they exhibit no sign of life. However, if they are in a live cell, some of the above-mentioned manifestations ascribed to living systems can be clearly discerned in them, e.g. metabolism, reproduction, etc.

The boundary between living and inanimate matter cannot be as yet delimited with accuracy, and thus it is also impossible to define the sub-

ject of biology with accuracy. In practice, however, this inaccuracy has been of no great consequence so far, since it is easy to decide in the predominant majority of cases, whether a system that exists in nature is living or inanimate.

A particular situation has recently arisen in connection with the development of cybernetics. It appears that even inanimate systems can show some kinds of behaviour which were formerly considered as criteria for the determination of living systems (e.g. excitability, self-organization, reproduction, etc.). Obviously, these criteria will have to be reinforced (i.e. the concept of a living system must be defined with greater precision) so as not to arrive at the paradox that an inanimate system "lives". We shall revert to this interesting problem in Chapter 17.

9.2 Branches of Biology

Every reader will certainly agree that the subject of biology (i.e. the investigation of the properties of living matter) is very extensive. This is caused primarily by the great complexity and ample differentiation of living matter. No wonder that the number of special branches in biology is so large that it is without analogy in any other fundamental scientific discipline. We must therefore first obtain a clear picture of the basic branches of biology.

All branches of biology are subordinate to *general biology* [C17, C39] which deals with phenomena common to all living systems. The other branches of biology, called *special branches*, can be classified from several points of view.

According to the kind of organism under investigation, we distinguish three basic branches of biology:

botany [C34] – which deals with plants,

zoology [C36] – which deals with all animals other than man,

anthropology – which deals with the study of man.

Cybernetics encroaches upon all three branches. We may say, however, that the classification given above is of little importance from the viewpoint of cybernetics.

Botany, zoology and anthropology can again be divided into three parts:

systematic – the classification of biological species,
structural – the study of biological systems from the viewpoint of their construction and functions,
evolutional – the study of biological systems from the viewpoint of evolutional changes.

Cybernetics overlaps to some extent only with the structural and evolutional biological sciences.

With the kind of phenomena investigated in living systems as a criterion, the structural biological sciences are divided into two extensive branches:

anatomy or *morphology* [C9, C31] – which deals with the shape of the elements and the manner of connection between them,
physiology [C12, C21, C35] – which deals with the relations between structure and behaviour.

On the whole, anatomy and cybernetics have no interests in common. A possible exception is microscopic anatomy, in whose sphere of interest we may encounter cases where the shape is simultaneously of great informational importance. However, there is a far closer relation between cybernetics and physiology.

Physiology can be divided, first of all, according to the resolution level at which the living organism is studied. At the molecular level we are concerned with *chemical physiology*, which, however, is more frequently called biochemistry [C14]. At the level concerned with cells (see Sec. 9.4) we speak of *cytology* [C6] (the study of the single cell as a system) or of *histology* (the study of cell systems – tissues) [C18, C26]. At a still higher level is the *physiology of organs (organologic physiology)*.

The cybernetic viewpoint for the definition of systems can be applied at all the levels mentioned. At the molecular level, for instance, cybernetics can be used in the study of processes in the course of which high-molecular compounds, especially proteins, are built up. In cells and tissues we are interested, from the cybernetic point of view, chiefly in the processes of self-organization (especially in nerve cells and nerve tissues) and the processes of reproduction and differentiation. In the physiology

of organs, cybernetics deals chiefly with the sub-divisions concerned with control systems. These are, in particular, neurophysiology (nerve control systems) [C12] and the physiology of the glands of internal secretion or endocrinology (glandular control systems) [C41]. Of course, cybernetics is also interested in the *physiology of receptors and effectors*.

All the special branches of physiology can also be divided into *normal* (the study of healthy organisms) and *pathological* (the study of diseased organisms). Here we distinguish between the *theoretical branches* (normal and pathological), and the *practical branches*, which comprise the most diverse *medical* or *clinical branches*. Cybernetics has its place in all these branches and it is desirable that the cybernetic approach be fully utilized. Thus, for instance, the pathological reproduction of cells, which is the cause of cancer, can be studied with advantage on cybernetic models of cells and tissues, especially with the aid of digital computers; the behaviour of damaged organs can be modelled by engineering systems, etc.

Let us return, in conclusion, to *evolutional biology*, which is divided into four basic branches:

ontogenesis – the study of the development of biological individuals,
genetics – the study of the relations between individual evolutional generations following upon each other in succession,
phylogenesis – the study of the development of species,
paleontology – the study of primeval, no longer existing biological systems.

Especially the first three of these branches will be observed to be related to cybernetics.

The classification of the biological sciences presented above is illustrated in Fig. 9.1 in the form of an oriented graph. The nodes of the graph pertain to the individual branches of biology, whereas the oriented connecting lines express the corresponding hierarchical relations between the given branches. Every path in the graph expresses (if we start from the initial node) a particular biological science, which might be further subdivided according to more special points of view. The branches which overlap with cybernetics are marked in red. Of course, the relations shown cannot be considered as final.

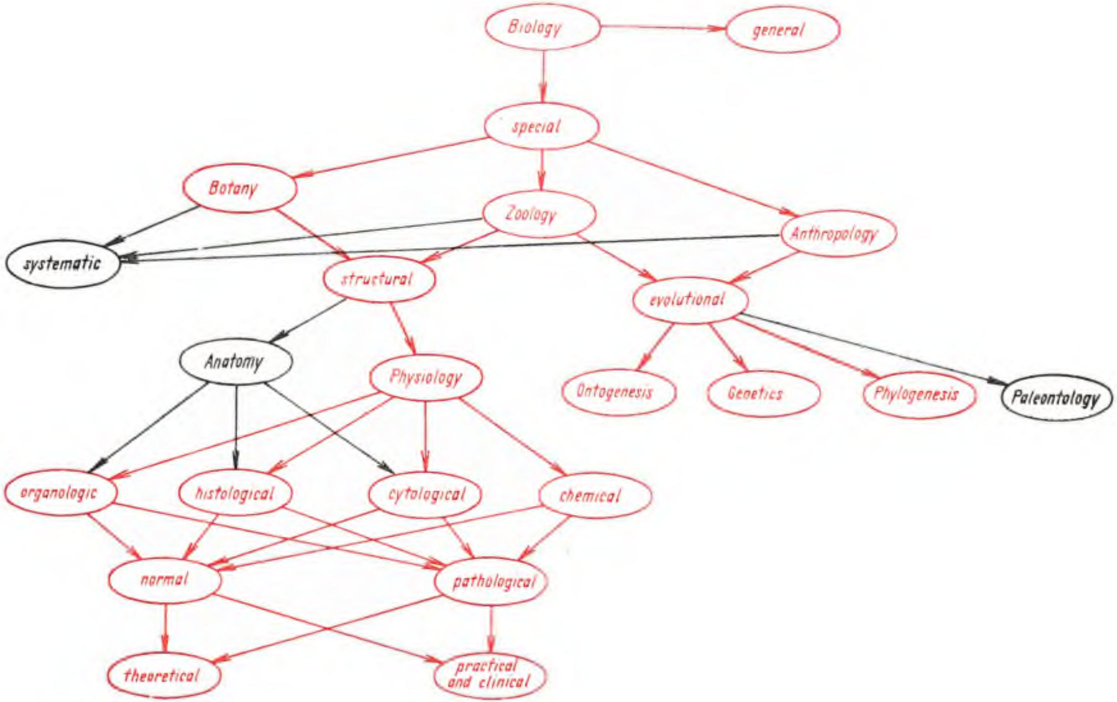

Fig. 9.1. Classification of biological sciences

9.3 Macromolecular Substances

We mentioned already in Sec. 9.1, that life is associated with the existence of certain high-molecular substances, even though it is not yet quite clear what complexes of these substances are necessary for life.

Organic high-molecular substances are immensely complicated chemical compounds (containing thousands to several hundred thousands of atoms of the individual elements), the detailed chemical structure of which is so far mostly unknown. We know, however, that they are composed – in accordance with certain rules – of several simpler low-molecular compounds. In this respect they differ from synthetic high-molecular substances (nylon, etc.), which are always made up of a single low-molecular compound.

High-molecular substances are made up mostly of only four chemical elements, namely carbon, hydrogen, oxygen and nitrogen. Other elements, chiefly sulphur, are represented in lesser amounts (about 1 to 2%).

We distinguish altogether three kinds of macromolecular compounds: *proteins*, *nucleic acids*, and *polysaccharides*.

According to our present state of knowledge, the substances most important to life seem to be proteins, nucleic acids, and their complexes – *nucleo-proteins*. Some of the simplest micro-organisms (e.g. viruses) appear to consist almost entirely of nucleo-proteins.

The fundamental components of the proteins are *α-amino-acids*, the chemical structure of which can be expressed by the general formula

$$\begin{array}{c} H \\ | \\ R - C - COOH \\ | \\ NH_2 \end{array}$$

The letter R in the formula stands for those groups of atoms (radicals), by which the individual amino acids differ from each other. We know altogether 20 different α-amino-acids which occur in proteins.

Polymer chains of proteins contain from several hundred to several thousand fundamental components – amino acids. If we assumed the

chain to consist of only 100 components, each of which may represent any one out of twenty possible amino acids, we would find that the number of different proteins can be theoretically as high as 20^{100}. This number indicates the gigantic variability offered by protein molecules. Nothing like all the types of proteins are represented in nature on our planet; the number of types of proteins on Earth is estimated at about 10^8 to 10^{10}.

The chemical differences between distinct types of proteins account for their functional (physiological) peculiarities, many of which do not yet appear to be known.

The basic general function of proteins is to maintain the specific properties of living individuals and of their parts, i.e. organs, tissues and cells. Every kind of living organism is characterized by certain types of proteins contained in it. Proteins are not interchangeable between species, i.e. the entry of strange proteins into the organism can, under certain circumstances, exert a disturbing effect on its structure.

Of immense importance to the correct control of metabolism are proteinaceous bio-catalysts called *enzymes* or *ferments*. There is a great number of them in living organisms; it is estimated at several hundred to thousands. Every enzyme is characterized by its accelerating a specific type of chemical reaction, i.e. it reduces its activation energy. The effectiveness of enzymes is many times (in some cases as much as a million times) higher than that of anorganic catalysts.

Other types of proteins produce the transformation of chemical into mechanical energy. They are found especially in muscles and in spermatozoa (male germ-cells). Plants, on the other hand, contain proteins which make possible the conversion of the luminous and thermal energy of the sun into chemical energy *(photosynthesis)*.

Proteins also form the basis of *hormones*, produced by the *glands of internal secretion (endocrine glands)* and carried by the blood to various parts of the organism. Their task consists in the control of various functions in living organisms; in this connection we speak of *glandular control* (see Sec. 9.8) as distinct from *nerve control* (Chapter 10).

Nucleo-proteins, i.e. complexes of specific proteins and nucleic acids, are of special importance to the reproduction of cells (see Sec. 9.4) and to the transfer of hereditary properties.

Nucleic acids are divided into two fundamental types:

1) *ribonucleic acids* – usually designated by the abbreviation *RNA*,
2) *deoxyribonucleic acids* – *DNA* for short.

The chemical structure of nucleic acids consists of a skeleton formed of phosphoric ribose (or deoxyribose) esters, to which four components are bonded. In *RNA* these are *adenine*, *guanine*, *cytosine*, and *uracil*; in *DNA*, *uracil* is replaced by *thymine*, the remaining components being the same as in *RNA*.

Polysaccharides occur in organisms either as reserves of energy, or as building materials.

From the cybernetic point of view it is desirable to devote great attention to high-molecular biological compounds. We are here concerned with molecular systems that are highly organized and thus act as carriers of a great amount of information. Information reveals itself in the specific behaviour of these systems and finds application in the interaction between systems of the same kind. Deserving special attention (from the cybernetic point of view) are, in particular, the control functions of enzymes, glandular control, the method of coding genetic information in DNA (see Sec. 9.6), and the signalling processes asserting themselves in the synthesis of proteins.

9.4 The Cell

One of the outstanding properties of living matter is that it occurs in the form of clearly delimited individuals. When studying them, we subdivide these individuals into separate organs and on them we define systems from various points of view. It appears that, in dividing a living individual into separate parts, some important properties characteristic of the given individual are lost. Some of the manifestations of life, however, e.g. metabolism, reproduction, growth, etc., may be maintained even in the separated parts. But the process of division can be carried only to a certain limit. This limit is represented by the *cell*, which is the basic unit of life capable of independent manifestations of life (single-cell organisms also exist).

Whether regarding the cell from the morphological, chemical, physical or cybernetic point of view, we always encounter a highly complicated microscopic structure (the dimensions of cells vary most frequently between the limits of from 10 to 100 μ).

In living organisms it is possible to find cells widely differing from each other, not only from the morphological, but also from the physiological aspect. This is the result of the process of differentiation which led to the specialization of individual cells. Aggregates of cells that perform a common physiological function are called *tissues*. These can be divided into:

1) *Various kinds of epithelia*, where we are most interested, from the viewpoint of cybernetics, in the tissues forming the substance of endocrine glands. The function of endocrine cells consists in that they produce, when excited by certain stimuli, a greater or lesser amount of specific substances called hormones. These are carried by the blood to different parts of the organs and act as control signals, thus forming the basis of glandular control (see Sec. 9.8).

2) *Muscular tissue*, which converts chemical energy directly into mechanical energy. It consists of elongated cells that are capable of contraction. The action of muscular tissue is mostly controlled by the nervous system (see Chapter 10). The study of the behaviour of muscle cells is of interest especially to bionics.

3) *Connective tissue*, which is of little importance from the cybernetic point of view.

4) *Nervous tissue*, where we are interested – from the cybernetic point of view – not only in the behaviour of individual cells but also in their role in the entire system of tissues (see Chapters 10 and 11).

Despite the considerable differentiation of cells there exist certain properties common to all cells. Every cell is composed of a semifluid substance, the *protoplasm*, which can be divided roughly into two distinct parts – the *nucleus of the cell (nucleoplasm)* and the *cytoplasm*. The nucleus is situated approximately in the centre of the cell and is usually of globular shape. It is separated from the cytoplasm by the nuclear membrane which is composed of molecules of some proteins and, apparently, some other substances. From the point of view of chemical

composition, the most important is deoxyribonucleic acid, the carrier of the genetic information that asserts itself in the reproduction of cells (see Sec. 9.6).

The protoplasm is a colloidal solution of high-molecular compounds that retains its structure only because of the large number of chemical reactions constantly taking place within it. These reactions can be divided, in principle, into two types:

1) *Exothermic reactions*, which are accompanied by the evolution of heat. They include all processes of disintegration, such as the fission of large molecules (e.g. proteins, polysaccharides, fats, etc.) into smaller ones.

2) *Endothermic reactions*, which are accompanied by the absorption of heat. These are reactions whereby large molecules are built up of smaller ones.

These two processes, however, are not in equilibrium, since the energy released by exothermic reactions is utilized not only for the corresponding endothermic reactions, but is partly consumed, for instance, in maintaining a constant body temperature, in the growth and reproduction of cells, and for the entire activity of the living organism. The difference between these two energies must therefore be supplied by the environment. In this respect we distinguish two kinds of organism:

1) *Autotrophic organisms* that are capable of converting the luminous and thermal energy of the sun into chemical energy *(green plants)*, or of obtaining energy by the oxidation of some anorganic compounds and performing the synthesis of organic substances with the aid of this energy (*fungi* and some *microbes*).

2) *Heterotrophic organisms (animals)*, which can accept their food only in a chemically highly organized form; i. e., they are dependent for food ultimately on autotrophic organisms.

Let us now return to the cell proper. Its existence is possible only under certain conditions. In multicellular organisms these conditions must be ensured by the environmental medium in which the cell is situated. The medium surrounding individual cells, frequently called the *internal environment* of the organism, must be stable.

Both the neural and the glandular control system take part in maintaining a stable internal environment. The executive factor in this process is the blood, which performs the following functions:

1. it carries the nutrients obtained from the food and the oxygen obtained by breathing to the cells of the whole organism,

2. it carries away the products of metabolism from the cells to the organs that discharge them (kidneys, liver, intestinal mucous membrane, skin, and lungs),

3. it distributes heat among the tissues and thus equalizes the temperature differences between individual organs,

4. it distributes substances which protect the tissues from various diseases,

5. it participates in glandular control by carrying the appropriate control signals (hormones) to the tissues concerned.

As will doubtlessly be clear from the foregoing explanation, systems can be defined at the cellular level from the most diverse points of view, by no means excluding the cybernetic point of view. These systems can be modelled by suitable means; the models can then be used to study different properties of cells. In some cases modelling has already proved successful (e.g. in tissue cultures, engineering and abstract models of nerve cells, etc.). In spite of this, the method of modelling does not seem to have been utilized in this branch so far to a sufficient extent.

9.5 THE PROBLEM OF THE ORIGIN OF LIFE

In Sec. 9.1 we have already mentioned the difficulties encountered when attempting to define living matter with accuracy. Moreover, the problem of defining living matter is closely associated with the problem of the origin of life. In solving this problem we must proceed by formulating partial hypotheses on the basis of all the available scientific facts; these hypotheses are then experimentally verified and elaborated on models.

One of the most perfect theories of the origin of life, that utilizes the entire body of scientific knowledge in this field accumulated up to the

present, has been formulated by the Russian biologist A. I. Oparin. We shall now present a short account of this theory.

Oparin starts from the fact that the elements occurring in living organisms have also been found to exist on other celestial bodies. Carbon, whose presence is of the greatest importance to living organisms, has been observed on all celestial bodies accessible to our investigations. In the hottest stars (with surface temperatures of up to 28 000°C) carbon occurs in the form of free, separate atoms. Spectroscopic investigations have shown, however, that already in our sun (with an average temperature of 6000°C) a certain amount of carbon exists in the form of the compounds C_2, CH and CN. This fact goes to show the astonishingly great capacity of carbon to form chemical bonds.

Since even more complicated hydrocarbons have been discovered in meteorites which reached the earth, it may be assumed that similar compounds have existed on the earth many ages ago. The great bond-forming capability of carbon has enabled various high-molecular compounds to be formed under specific conditions. The question remains, how life in the form now known has developed from these compounds.

When observing solutions of low-molecular compounds, their molecules will be seen to be distributed with absolute uniformity. Moreover, the uniformity of this distribution is stable, i.e. it does not become disturbed spontaneously. With an increasing size of molecules (from 0.1 to 0.0001 microns), colloidal solutions are formed, characterized by more complicated laws of behaviour. They are considerably less stable and their particles tend to combine and form complexes, in which the molecules of the individual substances in solution are linked in a certain manner. All molecules in a colloidal solution gradually concentrate in small droplets called *coacervations.*

Coacervations possess a very important property: the particles they contain are organized in a distinct manner even though this organization is initially very primitive and has a relatively low stability.

Another important property of coacervations is their capability of absorbing particles existing in their vicinity. The substances caught up in this manner can thus enter into chemical reactions with the substances of the coacervation proper, which is thereby enlarged and changes its chemical structure. The type and speed of these processes depends on

the physico-chemical structure of the original coacervation. Some of these processes help to increase the stability of the corresponding coacervation, others have the opposite effect.

Assuming that coacervations aggregated spontaneously in primeval oceans, it is easy to imagine their further development. It is clear that the only coacervations capable of maintaining their existence were those in which the speed of the chemical synthesis surpassed the speed of disintegration. In the opposite case, the coacervation did not persist and became the building material for more successful colloidal systems. Thus, the principle of natural selection found its application already in primitive colloidal systems, and led to their evolution in certain directions. This resulted in the formation of increasingly complex coacervations, with an ever-improving organization of their chemical reactions.

Successful coacervations went on increasing in weight and volume. As soon as their dimensions exceeded a certain limit, they started to divide as a result of various mechanical effects. Moreover, the individuals newly created in this process were organized in approximately the same manner as the original coacervation, and were again subjected to natural selection. Growth and evolution were possible only in those formations, in which not only the speed of the chemical reactions involved was increased, but where these reactions also acquired a certain organization. In the course of natural selection, simple anorganic catalysts were gradually replaced by ever more complex, efficient and specialized macromolecular catalysts. With their aid the coacervations were adapted to the faster acquisition of organic substances and thus to a more rapid growth and reproduction. By gradual evolution they thus acquired a property which might be called utility. At this stage of evolution we are already fully entitled to speak of life.

9.6 THE TRANSFER OF HEREDITARY INFORMATION

In recent times a number of results have accumulated which show that the carrier of hereditary (genetic) information is the *deoxyribonucleic acid (DNA)* found in the nucleus of cells. It appears that, on the one hand, *DNA* reduplicates itself (i.e. one system gives rise to two

equal systems), on the other hand it transfers information to the ribonucleic acid *(RNA)* which controls, in accordance with this information, the production of specific proteins. We are thus concerned with the following scheme of signal transfer:

$$\begin{array}{l} DNA \rightarrow RNA \rightarrow \text{protein} \\ \ \ \downarrow \\ DNA \end{array}$$

This scheme shows that we are concerned, in principle, with the explanation of three problems:

1) the principle of the reduplication of *DNA*,

2) how the information expressed by the structure of *DNA* is transferred to *RNA*,

3) the manner in which proteins are synthetized according to the information stored in *RNA*.

The first of these problems has already been clarified both theoretically and practically. This clarification is based on the model of the *DNA* molecule, suggested as long ago as 1953 by J. D. Watson and F. H. C. Crick [C19].

As already mentioned in Sec. 9.3, the specific peculiarity of each *DNA* molecule consists in the order in which the four nucleotides – adenine, guanine, cytosine and thymine – occur in it. These four nucleotides will be denoted by the symbols A, G, C, and T respectively. According to Watson and Crick, the *DNA* molecule consists of two chains of the aforesaid nucleotides, interconnected by a hydrogen bond. However, the hydrogen bond can be set up only between the pairs $A-T$ and $G-C$; it cannot be set up between $A-G$, $A-C$, $G-T$ and $C-T$. Under certain conditions, the hydrogen bonds can disappear. The two *DNA* chains then separate. By means of enzymes, free nucleotides can attach themselves to either of the two chains, but this can again happen only in the shape of the pairs $A-T$ and $G-C$. This is how one double chain of *DNA* reduplicates to form two equal double chains.

Similarly to the *DNA* molecule, the *RNA* molecule also consists of two chains of nucleotides linked by a hydrogen bond. Thymine, however, is replaced by uracil *(U)*. Hydrogen bonds can be set up only between the pairs $A-U$ and $G-C$ respectively. We see that *RNA*

can originate in *DNA*, but also that it can reduplicate itself or serve to produce *DNA*.

A more complicated and not yet fully clarified problem is that of the synthesis of a specific protein based on the information formed by the structure of *RNA*. The difficulty consists mainly in that, in *RNA*, information is coded of necessity in a manner different from that contained in proteins. This is because in *RNA* the information is represented by a sequence of four compounds (nucleotides), whereas in proteins we are concerned with a sequence of 20 components (amino acids). In principle, we are thus concerned with the problem of how to express information for a system using twenty-valued quantities by means of four-valued quantities. Moreover, we assume that the order of amino acids in the protein is determined by the order of nucleotides in *RNA*.

First of all, it is evident that at least three nucleotides must be used to determine a given amino acid, since $4^2 < 20 < 4^3$. It is more difficult to ascertain in which manner to read the nucleotide triplets in the *RNA* chain. Several types of code have been suggested so far, but none of them has been experimentally verified with definite validity. The most promising as yet is the so-called *comma-free code*. It is characterized by the fact that individual triplets do not overlap, while only some of the possible triplets (of which there are 64) have a distinct meaning. The principle is that the combination of two given triplets must not result in a triplet which would have some meaning. If, for instance, the code uses the two triplets $A_1A_2A_3$ and $B_1B_2B_3$, the triplets $A_2A_3B_1$ and $A_3B_1B_2$ must have no meaning, since they might be read out of the combination $A_1A_2A_3B_1B_2B_3$ by mistake. Similarly, the triplets $B_2B_3A_1$ and $B_3A_1A_2$, which might arise from the connection $B_1B_2B_3A_1A_2A_3$, must have no meaning.

Comma-free codes have been studied mathematically, and this investigation has led to an interesting conclusion: The number of triplets that can be formed for the comma-free code (assuming that every element of the code may acquire four values) is twenty, i.e. the same as the number of types of amino-acids in proteins. Even though this coincidence looks very convincing, some recent experimental work on synthetic ribonucleic acids has shown that the assumption of a comma-free code is not quite correct. That is to say, it appears that the same

amino acid can be determined by several different triplets of nucleotides. Ingenious experiments have led to the discovery of the assignment of some nucleotide triplets to the corresponding amino acids.

In any case, the problem of the transfer and coding of hereditary information cannot be said to have been solved yet. For instance, nobody has so far succeeded in proving that there exists a single universal genetic code common to all living organisms; we do not know whether the assumption is true according to which the order of amino acids in the protein is determined by the order of the nucleotides in *RNA*, etc. It is important, however, that research in this field is obtaining a clear object to concentrate upon. It is obvious that this problem concerns cybernetics to a considerable degree. Further study of these questions may be expected to lead to the discovery of some new principles whose modelling by inanimate systems may enormously contribute to engineering cybernetics.

9.7 Higher Functional Systems

An aggregate of tissues specialized to perform a specific function is called an *organ* (e.g. lungs, muscles, bones, heart, etc.). Individual organs depend upon each other, i.e. the existence of one depends on that of the other. Close cooperation exists between some organs. It is advantageous to regard such groups of organs and their mutual relations as systems, the behaviour of which has a certain unitary importance to the organism. The study of each of these systems forms the subject of a separate physiological specialization.

The number and kind of functional systems depends on the evolutionary stage of the organism involved. In the highest organisms, especially in man, it is possible to define – using a considerably simplified approach – nine fundamental functional systems: digestive, excretory, respiratory, motor, cutaneous, genital, circulatory, glandular and nervous. We must remember, of course, that this classification, although customary in physiology, is by no means the only possible one.

The most interesting from the cybernetic point of view are the two last of the systems listed above, i.e. *the glandular and the nervous system*. We shall therefore return to them later in the course of our exposition.

9.8 HOMEOSTASIS

Higher living organisms consist of a large number of cells. The human body, for instance, contains about 10^{13} cells.

Every cell is characterized by being – under certain conditions – capable of independent life. These conditions are determined by the medium in which the cell is located. In the living organism this medium is called the *extracellular* fluid as distinct from the *intracellular* fluid contained in the cell. The extracellular fluid consists of tissue fluid, blood plasma, and other components.

The existence of cells is a condition for the existence of the living organism. The organism must therefore be arranged so that its internal medium remains stable. All processes which help to maintain a stable internal medium are summed up under a common term – *homeostasis.*

The systems ensuring homeostasis can be divided roughly into three groups:

1) *Systems effecting physico-chemical regulation directly in the tissues concerned.* In this case we are concerned with the control of the speed of individual types of chemical reactions, on the basis of the ratio between the concentration of the substrata and of the products of cellular reactions. The speed of the reactions is controlled by enzymes.

2) *The autonomic regulation systems of individual organs.* These include, for instance, the adaptation of receptors in dependence upon stimuli, the opening of capillaries supplying muscle tissue with nutrients in dependence upon muscular activity, the autonomic regulation of the heart muscle, etc.

3) *Centrally controlled systems* which create conditions favourable to the organism as a whole. There are usually several centres, with hierarchic relations between them. According to the manner in which control signals are transmitted, two typical systems of this class can be distinguished:

a) the *nervous system,* where signals are transmitted over nerve fibres by electric pulses,

b) the *glandular system,* where signals are transmitted through the blood circulation system by chemical compounds.

An explanation of the nervous system, which is very complicated, is left to the two subsequent separate chapters. We shall now present a brief outline of the glandular system.

The control centres of the glandular system are the *glands of internal secretion (endocrine glands)*. These glands produce substances called hormones, and transfer them to the blood. The blood transports specific

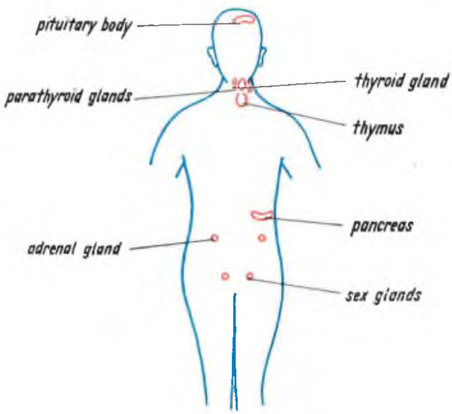

Fig. 9.2. Location of endocrine glands in man

hormones to those tissues which are sensitive to their action. There they affect mainly the activity of enzymes, their arrangement in the cells, and the permeability of the cell membrane. However, the exact nature of the effect produced by hormones has not yet been satisfactorily clarified.

The human body comprises six basic glandular centres (endocrine glands). These are the *pituitary body*, the *thyroid gland*, the *parathyroid glands*, the *thymus*, the *islets of Langerhans*, the *adrenal gland*, and the *sex glands*. The approximate location of the individual glands is shown in Fig. 9.2.

The function of the endocrine glands is controlled in several different manners:

1) *Direct control by the nervous system* with the aid of so-called secretory nerve fibres (e.g. the discharge of adrenalin from the adrenal gland),

2) *indirect control by the nervous system*, i.e. the control mediated by one or several glandular elements (e.g. the function of the thyroid gland),

3) *chemical control* by the concentration of some specific substance in the blood, which flows through the corresponding endocrine gland (e.g. the concentration of calcium controls the secretion of parathormone by the parathyroid glands),

4) *hybrid control*, i.e. simultaneous nervous and chemical control (e.g. the secretion of insulin from the pancreas).

9.9 THE HOMEOSTAT

Homeostasis is one of the characteristic features of living systems. It is therefore interesting that this action has been successfully imitated by an inanimate system as long ago as 1947. This device, which models simple homeostasis and which was invented by the English psychiatrist W. R. ASHBY, is called "homeostat".

The *homeostat* has been described in the majority of books dealing with cybernetics, e.g. [A2, A9]. For this reason we are not going to discuss its construction, but shall deal only with the essence of the matter.

From the point of view of a very low resolution level, the homeostat is made up of two systems denoted by $\mathbf{S}_1$ and $\mathbf{S}_2$ respectively. The system $\mathbf{S}_1$ models, substantially, the following system of differential equations:

$$\begin{aligned}
\frac{\mathrm{d}x_1}{\mathrm{d}t} &= k_{11}x_1 + k_{12}x_2 + k_{13}x_3 + k_{14}x_4 \\
\frac{\mathrm{d}x_2}{\mathrm{d}t} &= k_{21}x_1 + k_{22}x_2 + k_{23}x_3 + k_{24}x_4 \\
\frac{\mathrm{d}x_3}{\mathrm{d}t} &= k_{31}x_1 + k_{32}x_2 + k_{33}x_3 + k_{34}x_4 \\
\frac{\mathrm{d}x_4}{\mathrm{d}t} &= k_{41}x_1 + k_{42}x_2 + k_{43}x_3 + k_{44}x_4 ,
\end{aligned} \tag{9.1}$$

whereas system $\mathbf{S}_2$ is capable of randomly varying the coefficients k_{ij} under certain assumptions.

The task of the homeostat is to satisfy the inequalities

$$|x_i| < K \tag{9.2}$$

for all values of $i = 1, 2, 3, 4$; K is a given number. As soon as some of the variables x_i stops satisfying the inequality (9.2), system $\mathbf{S}_2$ randomly changes the coefficients k_{ij} and thereby effects a change in system (9.1). It continues doing so until it finds such coefficients k_{ij} (provided this is possible, of course), for which system (9.1) permanently satisfies the conditions (9.2).

It is obvious that the systems (9.1) and (9.2) can be simulated by analogue computers (see Chapter 6). It is thus sufficient to connect to an analogue computer a discrete system which, in accordance with the given conditions (9.2), effects either random or programmed changes in system (9.1) until the conditions (9.2) are satisfied. Such equipment can then also be used to solve problems in homeostasis, presented in a different manner. Practical experiments in this field have been performed by G. V. SAVINOV[B 62].

CHAPTER 10

THE NERVOUS SYSTEM

The nervous system is the supreme control organ, and is found only in living organisms at higher stages of evolution. It processes an enormous amount of information obtained, on the one hand, from the environment of the organism, and on the other hand from its internal organs. The method (or algorithm) whereby this information is processed corresponds to the general requirements of the organism and adapts itself very elastically to changing conditions. The nervous system is therefore rightly considered to be the most perfect cybernetic system yet known. The increasingly detailed knowledge of this system will no doubt be of great importance to the perfection of mankind as well as to the development of engineering.

In this chapter we want to present to the reader a survey mainly of those features of the nervous system which are related to cybernetics. With regard to the great extent of this theme, the exposition to follow must be regarded as purely informative. For a more profound study of the nervous system in all its aspects we recommend, e.g., the book listed under Ref. [C12].

10.1 A SURVEY

The fundamental element of the nervous system is the *nerve cell*, also called *neuron*. The properties of the neuron will be dealt with in Sec. 10.2 et seq. The number of neurons in the nervous system depends on the species of the organism involved; in the human body it varies between 3.10^9 and 10^{10}.

In different parts of the nervous system, neurons are specialized for various functions. In this respect, the nervous system can be divided into:

1. *Receptor nerves*

a) *Exteroceptors* – neurons that transform signals arriving in the organism from the environment into neural excitations (see Sec. 10.3). There exists a still finer specialization according to the kind of signals received (chemoreceptors, photoreceptors, thermoreceptors, mechanoreceptors).

b) *Interoceptors* – neurons that transform signals concerning the state of internal organs (e.g. muscles, blood vessels, the respiratory tract, etc.) into neural excitations.

2. *Effector nerves*

a) *Motor neurons* – which control muscle action.

b) *Secretory neurons* – which control the action of the endocrine glands.

3. *The nervous system proper*

a) *Autonomic nervous system.* Its main task is to maintain universal homeostasis, especially in cooperation with the glandular system, the interoceptors and the central nervous system. It consists of a large number of smaller nervous systems located primarily in various internal organs and in their vicinity. It is divided into the *sympathetic* and the *parasympathetic* systems, which act in opposite ways (for instance, the sympathetic system supports catabolism, the parasympathetic system supports anabolism, etc.).

b) *Central nervous system.* This is the supreme co-ordinating nervous system which maintains the functional integrity of higher living organisms and controls their behaviour so that they are adapted to the given conditions in the most advantageous manner. The central nervous system consists of the *spinal cord* and the *brain*; the latter, in its turn, is composed of a hierarchy of partial systems (see Sec. 10.5). The central nervous system is entered by signals from the exteroceptors and interoceptors; from it there emerge signals leading to the motor and secretory effectors and to the centres of the autonomic nervous system.

10.2 THE NEURON

Every neuron (nerve cell) consists of the cell body and the nucleus *(perikaryon)*, with several incoming nerve fibres *(dendrites)* and a single outgoing nerve fibre *(neurite* or *axon)*.

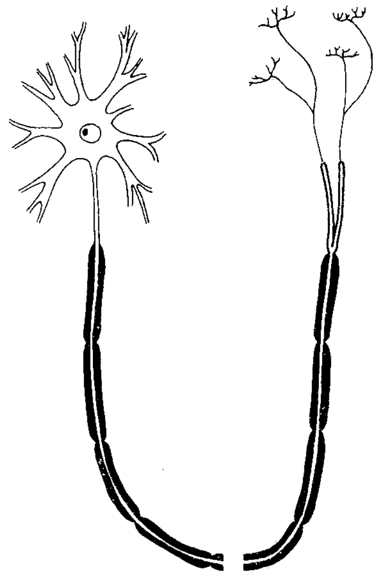

Fig. 10.1. Typical shape of neuron

Neurons can be of different shape; the shape most frequently encountered is illustrated in Fig. 10.1. The dendrites are usually shorter (with a length of the order of several millimetres), whereas axons sometimes attain a considerable length (even exceeding 1 metre), their ends being usually branched.

Large numbers of nerve fibres are made up into bundles which we call *nerves*. These are organs having their own supporting and protective tissue and their own blood supply. In addition, nerve fibres are enclosed in sheaths which ensure, on the one hand, the mutual insultation of the fibres, and on the other hand contain sources of energy required to ensure the propagation of neural impulses (see Sec. 10.3).

The cell body of the neuron is usually about 0.1 mm in size. The diameter of the nerve fibres varies between 0.001 and 0.02 mm.

Neurons do not reproduce in the grown-up organism. Their number thus remains constant or diminishes, since damaged neurons do not regenerate. Moreover, a considerable number of neurons degenerate spontaneously – by ageing.

It is of interest to note, that the metabolism of the dendrites and also that of the very long axons is maintained by the cell body of the neuron. If some part of the neuron separates from the cell body, this necessarily leads to its degeneration and destruction.

10.3 Excitation

Neural excitation consists of an impulse based on an electrochemical process arising in the neuron. Its generation depends on several factors:

1) the state of the internal medium in which the neuron is located (in this respect the preceding action of the neuron is also of importance),
2) the state of the input synapses (see Sec. 10.4),
3) the combination of signals (excitations) applied to the input synapse at the given instant; moreover, signals at some inputs may be excitatory, i.e. supporting the creation of the excitation, whereas signals at other inputs may be inhibitory, i.e. preventing excitation.

The neuron is a two-state element: it is either in the inhibited or in the excited state. All excitations in a particular neuron have approximately the same properties. The magnitude of certain quantities is expressed in receptor nerves, for instance, by the frequency of the neural impulses, the properties of individual impulses remaining more or less unchanged.

The characteristic waveform of a neural impulse is shown in Fig. 10.2. The impulse attains an amplitude of approximately 50 mV and has an average duration of 1 millisec.

Neural impulses are propagated over the nerve fibres at speeds of from 1 to 120 metres per second, this speed being roughly directly pro-

portional to the diameter of the fibre. No attenuation occurs in the course of transmission, since the energy is constantly being replenished from the nerve fibre's own chemical sources. The transmission of the neural impulse is based on a complicated electrochemical process which is independent of the function of the particular neuron. An interesting peculiarity (especially when compared to engineering systems) consists in that – owing to the synaptic junctions – every nerve fibre conducts impulses in one direction only and transmits information of

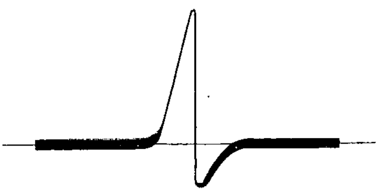

Fig. 10.2. Waveform of neural impulse

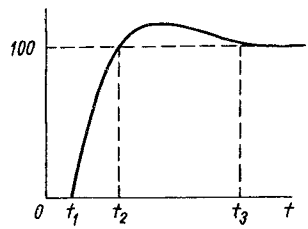

Fig. 10.3. Excitability of neuron following upon stimulation

only one type. According to the direction in which impulses are conducted by the nerve fibres, we distinguish *centripetal or afferent and centrifugal or efferent nerve fibres.* The former conduct neural impulses from the peripheral regions to the centre, the latter transmit impulses in the opposite direction.

As soon as the neural impulse begins, the neuron undergoes a number of changes. For a certain interval following stimulation (the so-called *refractory phase*) the neuron acquires properties different from its normal behaviour. The excitability in this period can easily be expressed graphically (see Fig. 10.3). The time t is plotted on the x-axis, the excitability of the neuron – expressed in per cent – on the y-axis, 100% corresponding to its normal excitability. Prior exitation is assumed to have terminated at the instant $t = 0$. The period t_1 (2 millisec. on the average) is called the *absolute refractory period,* the interval from t_1 to t_2 (about 8 millisec.) is termed the *relative refractory period,* and the interval between t_2 and t_3 (about 15 millisec.) the period of increased excitability.

10.4 SYNAPSES

Synapses are special formations which effect the functional connection of two neurons *(intercellular junction)*. Morphologically, the synapse forms either the junction between a branch of the axon of one neuron and the dendrite of another neuron *(axo-dendritic synapse)*, or between a branch of the axon of one neuron and the cell body of another neuron *(axo-somatic synapse)*. The nervous systems of primi-

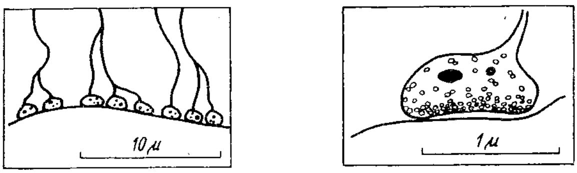

Fig. 10.4. Shape of axo-somatic synapse

tive animals contain only axo-dendritic synapses, whereas axo-somatic synapses predominate in the central nervous systems of higher animals. In a wider sense, the functional junctions between the terminal sections of axons and effectors (e.g. in motor end-plates, in which a motor nerve terminates in a muscle), and between the receptors and the dendrites associated with them are also considered as synapses.

In every synapse we distinguish the *presynaptic part* (the characteristic termination of an axon branch), the *postsynaptic part* (dendrite or cell body) and the *synaptic gap*, 100 to 500 Å in width. The approximate shape of axo-somatic synapses is illustrated in Fig. 10.4 in two different magnifications. The cytoplasm of the presynaptic part contains, on the one hand, tiny formations – *mitochondria* (concentrated chiefly near the synaptic gap), and on the other hand larger, approximately spherical bodies – *synaptic vesicles*, having a diameter of from 300 to 500 Å. It has been shown experimentally that these formations, which contain specific substances of proteinaceous nature *(mediators)*, are of the greatest importance for the creation of the neural impulse, since they are capable of chemically changing the permeability of the synapse.

Let us now note the fundamental properties characterizing the synapse:

1. Synapses act in one direction only, i.e. the impulse in the presynaptic part affects the rise of the neural impulse in the neuron to which the postsynaptic part belongs, but the converse does not apply.

2. Signals are delayed in the synapse by from 0.5 to 30 millisec., according to the type of neuron.

3. The postsynaptic neuron is activated to the level of the neural impulse at a certain instant only when the impulses in the presynaptic parts are suitably combined. These combinations may, however, gradually change, depending on how frequently the individual synapses are activated.

4. Some synapses do not directly affect the activation of the neuron, but they influence other synapses which then have a stronger effect. This phenomenon is called facilitation. It is well known that many neurons, especially in the central nervous system, do not activate other neurons directly, but that they effect only their facilitation by impulses repeated at regular intervals.

5. Synapses (as distinct from nerve fibres) show a marked fatigue in that their effect on the action of the postsynaptic neuron gradually decreases with the continued arrival of new excitations. If no excitations arrive, the synapse recovers. There are considerable differences between neurons as regards the fatigue resistance of the synapses and their speed of recovery. The speed of fatigue and recovery also depends on the momentary metabolic facilities of the corresponding neuron.

10.5 The Central Nervous System

Fig. 10.5 shows the block diagram of a living individual regarded as a cybernetic system at a low resolution level. The illustration clearly indicates the linkages between the central nervous system and the other elements of the entire cybernetic system.

The *central nervous system* (henceforth denoted, for brevity, by the abbreviation CNS) is found only in higher animals, especially in verte-

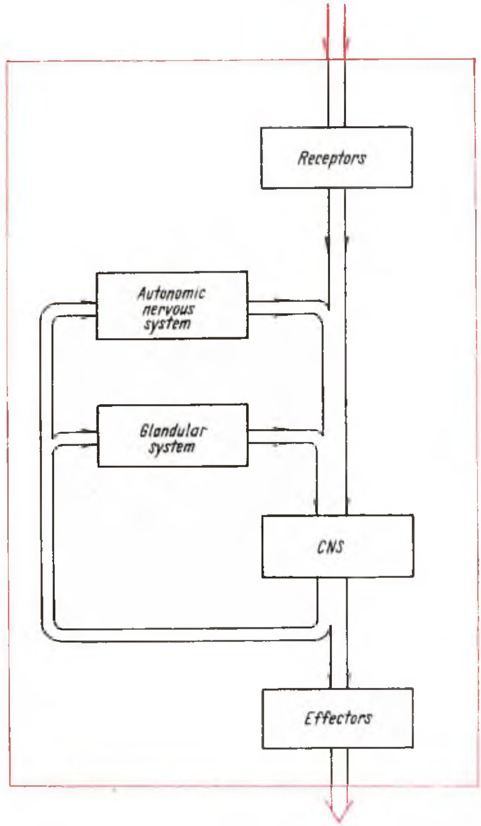

Fig. 10.5. Living individual regarded as a cybernetic system

brates. In man it can be divided – both functionally and anatomically – roughly into seven basic parts:

1) *spinal cord*,
2) *spinal bulb (medulla oblongata)*,
3) *little brain (cerebellum)*,
4) *midbrain (mesencephalon)*,
5) *betweenbrain (diencephalon*, including the *thalamus* and *hypothalamus)*,
6) *corpus striatum*,
7) *cerebral cortex*.

The spinal cord is a bundle of nerve tissue about 1 cm in diameter and 50 cm in length, contained in the spinal canal and surrounded by the cerebrospinal fluid which damps all shocks and thus protects the spinal cord from damage. The remaining parts of the CNS (including the spinal bulb) are housed in the head, namely in the cranial cavity which is bounded by strong bones and also filled with cerebrospinal fluid. The common name used for these parts of the CNS (i.e. except the spinal cord) is the *brain.*

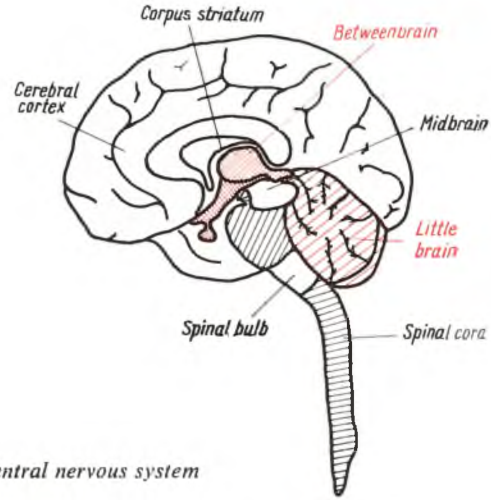

Fig. 10.6. Subdivisions of the central nervous system

In the CNS the principle of functional hierarchy asserts itself. This is closely connected with the phylogenetic evolution of its individual parts. The action of the phylogenetically younger parts is functionally always superior to that of the phylogenetically older parts. The spinal cord, as the phylogenetically oldest part, is in this sense subordinate to the spinal bulb, the spinal bulb to the little brain, etc., in the order in which we listed the individual parts. The supreme control unit is the cerebral cortex.

It is of interest to observe that the morphological hierarchy is in agreement with the functional hierarchy. As seen in Fig. 10.6 the spinal cord is placed lowest, the spinal bulb higher, etc., and the cerebral cortex at the highest spot.

The basic element of function in the CNS is the *reflex circuit*, also called *reflex arc*. The elementary reflex represents a single stimulus-response pair mediated by the CNS. The reflex arc consists of a receptor (sense

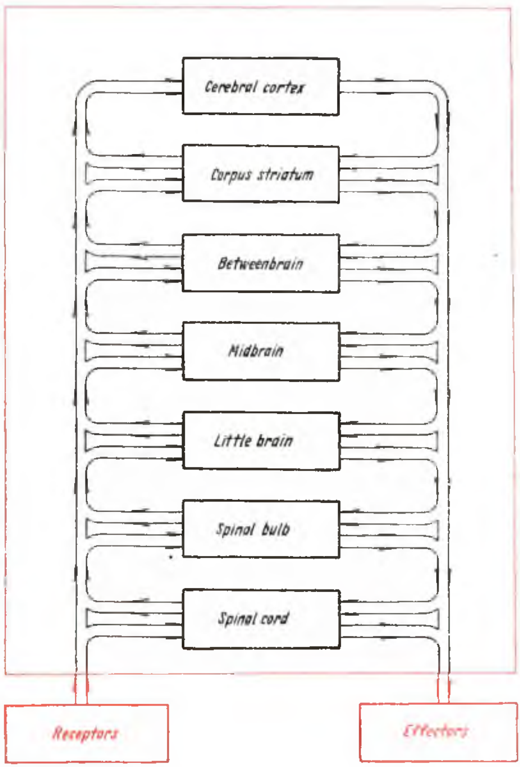

Fig. 10.7. Functional relations between individual parts of the CNS

organ), afferent nerve fibres, certain parts of the CNS, efferent nerve fibres and an effector (executive organ).

Reflexes can be classified from various points of view. According to whether we are concerned with a contact with the environment of the organism or with its internal organs, reflexes are divided into somatic (involving exteroceptors) and autonomic ones (involving interoceptors).

According to the position of the part of the CNS involved, they are divided into spinal and cerebral reflexes. According to whether they are innate or acquired, we divide them into *unconditioned* and *conditioned reflexes*.

Let us remind the reader that, besides the French scientist RENÉ DESCARTES, a great contribution to the foundation of the reflex theory was made by the Czech physician JIŘÍ PROCHÁZKA (1749 – 1820) by his work [C30] written in Latin and published 1784 in Prague. The reflex theory was then further developed on the basis of new experimental discoveries, especially by the Russian physiologic school. In this connection we would like to mention the outstanding pioneering work of I. M. SECHENOV (1829 – 1905), who is regarded as the founder of modern Russian physiology. The evolution of the reflex theory was completed by I. P. PAVLOV (1849 – 1936) who achieved fame chiefly by his discovery of the conditioned reflex.

Now let us note the functional relations between individual parts of the CNS. They are illustrated in Fig. 10.7 in a simplified form. It will be seen that every part is connected with the subordinate as well as with the superior parts. Links leading to the superior parts are called *afferent*, those to the subordinate parts *efferent*.

It is of interest that a great part of our present knowledge on individual parts of the CNS is related to their hierarchic arrangement, roughly in the sense that the higher the part considered, the less we know about it. Let us now briefly summarize the present fundamental physiological knowledge concerning individual parts of the CNS.

The *spinal cord*. At the present, this is the part of the CNS that has been most thoroughly investigated from the experimental point of view. Fig. 10.8 shows its cross-section, illustrating the front and rear bunch of nerve fibres, the region of grey matter (cell bodies of the neurons) and the region of white matter (afferent and efferent nerve fibres). The rear bunch contains only afferent fibres, the front bunch only efferent fibres. The spinal cord comprises altogether 32 pairs of front bundles and an equal number of rear bundles.

An excitation penetrating into the spinal cord through some of the afferent fibres of the rear bunch can either, after having passed through several spinal neurons (sometimes only a single neuron), leave the spinal

cord through some efferent fibre of the front bunch, or can proceed through some afferent fibre in the white spinal matter into the brain. After travelling over a more or less complicated path in the brain it can then return over an efferent fibre into the spinal cord and hence emerge through some fibre of the rear bundle into an executive organ.

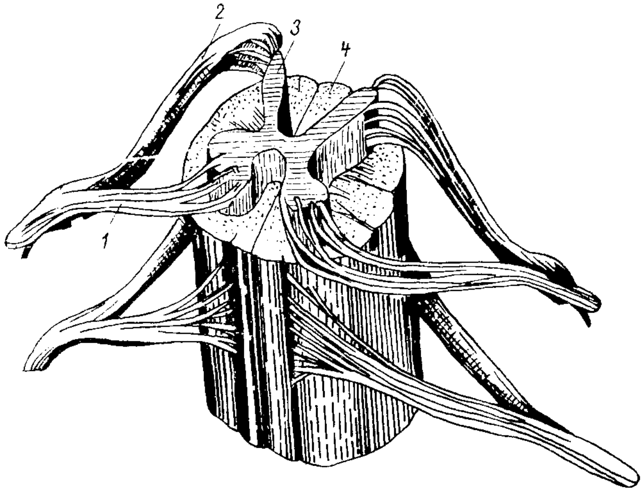

Fig. 10.8. Cross-section of spinal cord

1 — Front bunch. 2 — Rear bunch.
3 — Grey matter. 4 — White matter.

We may thus say, in a figurative sense, that some lower control functions are performed directly by the spinal cord, whereas the more complicated functions are left to the higher parts of the CNS. In the spinal cord we are concerned, without any exception, with unconditioned reflexes.

The *spinal bulb*. This performs some important functions indispensable to life:

1. It controls the action of the blood circulation system, the respiratory system and the digestive system.

2. It gives rise to some important defence reflexes, such as vomiting, cough, sneezing, etc. It is true that the movements associated with these

reflexes are controlled by the spinal cord, but the commands for their performance are issued by the spinal bulb.

3. It is the centre from which the movements of the facial muscles are controlled, i.e. it also asserts itself in speech.

4. Together with the little brain, the midbrain and other organs it ensures the maintenance of the normal body posture.

The functions listed above show the fundamental importance of the spinal bulb to the conservation of life. Damage to this organ (e.g. breaking of the cervical vertebrae) usually results in immediate death by suffocation.

The *little brain*. On the basis of present knowledge, the function of the little brain can be expressed as follows:

1. It causes a constant tonus in the skeletal muscles and thus participates in maintaining the upright posture.

2. It controls the co-ordination of more complicated movements, i.e. maintenance of balance in walking, speech movements, etc.

The cerebellum, although an organ not indispensable to man, is still of great importance to his normal activity. The cessation of its function leaves permanent and significant consequences, but it is not a cause of death. Temporary disturbances of the little brain can be caused by alcohol and other narcotics. They reveal themselves as disturbances in walking, speech, and in the co-ordination of movements.

The *midbrain*. This consists predominantly of white matter, containing afferent and efferent nerve fibres. However, it also comprises a smaller amount of grey matter, whose neurons control eye movements (defence reflexes, contraction of the pupil in response to strong light, etc.), mediate unconditioned auditory reflexes (turning of the head to the direction of sound, etc.) and permit regaining of the upright posture lost, for instance, by a fall, etc.

The *betweenbrain*. This contains two parts performing different functions: *thalamus* and *hypothalamus*. It has already been verified experimentally, that the thalamus processes all excitations arriving from both exteroceptors and interoceptors, resulting in various sensations (such as those of touch, pain, smell, taste, etc.) and emotions (e.g. fear, gaiety, etc.). The proper nature of these sensations and emotions has not yet

been clarified from the physiological point of view. It is known, however, that the cerebral cortex also participates in them.

The hypothalamus is the centre which co-ordinates all vegetative functions, e.g. blood circulation, temperature regulation, respiration, etc.

Corpus striatum. This part, as shown in Fig. 10.7, lies immediately beneath the cerebral cortex. It serves as a means of transformation, which controls the goal-seeking function of the skeletal muscles according to orders from the cerebral cortex.

Cerebral cortex. This is phylogenetically the youngest and functionally the most complicated part of the CNS. It performs all functions summed up under the name of higher nervous activity. It is the highest and most perfect centre for the co-ordination of the external and internal functions of the organism. The fundamental element of action of the cerebral cortex is the conditioned reflex.

The cerebral cortex consists of two hemispheres having more or less the same functions. In man it fills up the greater part of the cranial cavity and comprises about half the number of all neurons.

Three types of neuron links can be distinguished in the cerebral cortex:

1. *association fibres* – connecting neurons within the same hemisphere,

2. *commissural fibres* – connecting corresponding areas in the two hemispheres,

3. *projection fibres* – connecting the cortex with lower parts of the CNS.

CHAPTER 11

MODELLING OF THE NERVOUS SYSTEM

In speaking of the modelling of the nervous system, three basic aspects must be distinguished:

a) the exact analysis of processes in nerves with the aid of mathematical methods,
b) models of neurons,
c) models of neuron networks, which are very closely associated with the problem of logic nets (see Chapter 8).

In this chapter we want to describe some theoretical and engineering aids used, on the one hand, for the cybernetic modelling of the nervous system in the sense of aspects b) and c), on the other hand for modelling some of its manifestations, particularly unconditioned and conditioned reflexes.

When speaking of models of reflexes, whether unconditioned or conditioned, it is on the whole evident that in this case we are concerned with models of behaviour. We must realize, of course, that to a greater or lesser degree we are simultaneously concerned with models of systems. If we say "to a greater or lesser degree" we are thinking of different resolution levels, at which the model of behaviour also appears as the model of the system. We know already that this is always true for the lowest resolution level. Therefore, the situation becomes interesting only at higher resolution levels. As we shall see (e.g. in the models of conditioned reflexes), a particular specific behaviour may be determined by certain fixed structures at all resolution levels below a certain limit. In the models treated in Sec. 11.1, this limit is very low. However, if we use models of neurons (see Sec. 11.2) for modelling manifestations of the nervous system, then the model of behaviour may simultaneously become a model of structure even at a considerably high resolution level (see Sec. 11.3).

11.1 Models of Reflexes

In principle, the engineering *modelling of an unconditioned reflex* is very simple. It consists in that a certain stimulus (e.g. mechanical pressure, sound, light, etc.) is transformed by means of a specific sensor (e.g. a pushbutton, microphone, photoelectric cell, etc.) and, if

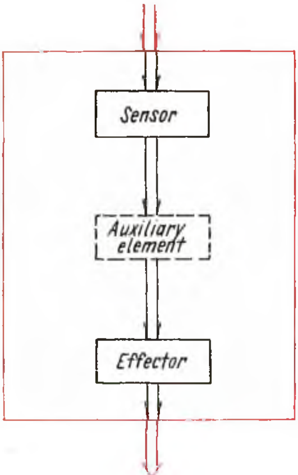

Fig. 11.1. Block diagram of the model of an unconditioned reflex

necessary, with the aid of another intermediate element into a form in which it is capable of controlling some kind of effector (e.g. an electromotor, lamp, audio-frequency generator, etc.). The general block diagram of the model of an unconditioned reflex is shown in Fig. 11.1.

A simple device modelling an unconditioned reflex is presented, for instance, by an electromagnet which controls the flow of a liquid through a pipe. The stimulus enters the winding of the electromagnet in the form of an electric current, is transformed into a magnetic flux, and in this form actuates the mechanism which opens and closes the pipe.

As a matter of interest, a combinatorial system having a rather complicated behaviour can be formed on the basis of the models of several unconditioned reflexes alone. The first cybernetic models of living organisms, now regarded as simple cybernetic toys, were also based on this principle. These models, named after various animals (tortoise, squirrel,

etc.) are usually fitted with a motion device which can be controlled by various stimuli. These models are capable, for instance, of going round obstacles, of reacting to light or sound by changing the direction of their motion, etc.

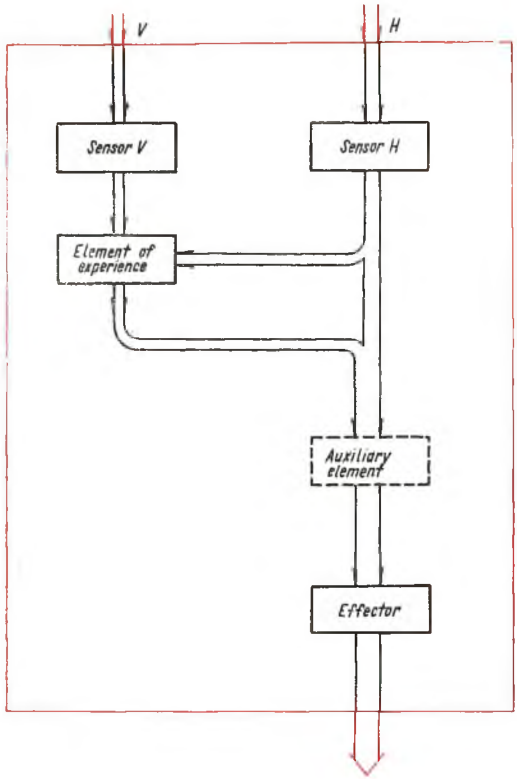

Fig. 11.2. Block diagram of the model of a conditioned reflex

More complicated and of greater interest are *models of conditioned reflexes*, the block diagram of which is presented in Fig. 11.2. Every model of a conditioned reflex must necessarily have the structure shown in this illustration. The nucleus of this structure consists of an element of experience which, under certain conditions, connects the secondary stimulus V from the corresponding sensor to the effector, if necessary

via an auxiliary element. We have already encountered this problem in Chapter 8, where we presented an example of the synthesis of a model of a conditioned reflex given by a certain graph of behaviour. There are no obstacles to designing, in a similar manner, a discrete system modelling some differently defined conditioned reflex.

However, conditioned reflexes can also be modelled by continuous systems. An example of such a model is shown in Fig. 11.3. The main and the secondary stimulus are modelled by the switches H and V respectively, the response shows in the form of a positive electrical potential at terminal R. The simultaneous action of both the stimuli V and H is recorded by the capacitor C being charged via resistor R_1. The increase of voltage across the capacitor results in a reduction of the negative grid bias of the electronic valve, and the latter passes a larger current. If the voltage across the capacitor exceeds a certain limit, the current flowing through the valve will be sufficient to actuate the relay Z, whose coil is in the anode circuit of the valve. The relay has a contact which, when closed, causes the response R to appear not only as a result of stimulus H, but also as that of stimulus V alone. The charged capacitor is simultaneously discharged via resistor R_2, this action representing the extinction of the conditioned reflex.

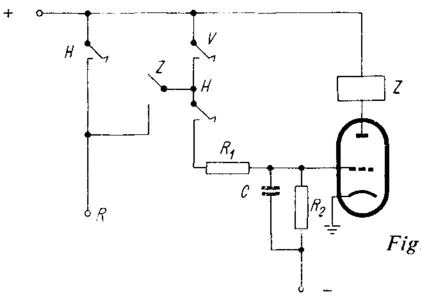

Fig. 11.3. Example of modelling a conditioned reflex by a continuous system

Similar circuits have been used to expand the capabilites of the simple cybernetic models already mentioned in connection with unconditioned reflexes. Such a model will then be capable not only of going round obstacles with which it collides, but also of learning how to react correctly to a suitable warning signal. If it is warned, it will avoid the obstacle without colliding with it.

A great number of devices modelling several unconditioned and conditioned reflexes and fitted with motion drives have already been described in literature [B18, B63, B71, B87]. Even though their epistemologic significance is not very great, these devices have nevertheless shown that even rather complicated patterns of behaviour can be modelled with the aid of a small number of elements.

All models of conditioned reflexes so far presented we based on the assumption that the stimulus V triggers a response R only under certain accurately defined and reproducible conditions. Actual experiments have shown, however, that these conditions vary in a random manner within certain limits. This fact can very well be taken into account when modelling a conditioned reflex a in digital computer. Let us introduce, for this case, a number C_i and let us assume that the stimulus V leads to a response R only if the inequality $C_i > K$ is satisfied, where K is a given constant. Upon every change of stimulus, the number C_i is transformed into a number C_{i+1} according to the relation

$$C_{i+1} = C_i + g + h\,, \tag{11.1}$$

where g is a random quantity statistically defined in a certain way and h a quantity depending upon the kind of stimulus in the following manner:

$$h = \begin{cases} 0 & \text{for } V = 0 \\ |h_1| & \text{for } V \neq 0 \text{ and } H \neq 0 \\ -|h_1| & \text{for } V \neq 0 \text{ and } H = 0\,. \end{cases} \tag{11.2}$$

Under these assumptions, the rise and extinction of a conditioned reflex can be modelled by a relatively simple algorithm, whose block diagram is shown in Fig. 11.4.

Digital computers can also be used to model sets of conditioned reflexes and their different mutual relations. It is then also possible to observe the creation of conditioned reflexes of higher order, i.e. those depending on other conditioned reflexes. Modelling of this kind appears to offer great promises to the future development of neurophysiology, psychology and engineering. The German scientist Prof. STEINBUCH [B68, B69, B70] and some other workers in this field, who are attempting to model complicated sets of conditioned reflexes by specialized engineering systems, are following a different path.

In his models, K. STEINBUCH uses as basic element a conductivity matrix, illustrated in Fig. 11.5. It is made up of horizontal conductors $h_1, h_2, \ldots, h_s$ and vertical conductors $v_1, v_2, \ldots, v_t$. Every horizontal conductor h_i $(i = 1, 2, \ldots, s)$ is connected with every vertical conductor

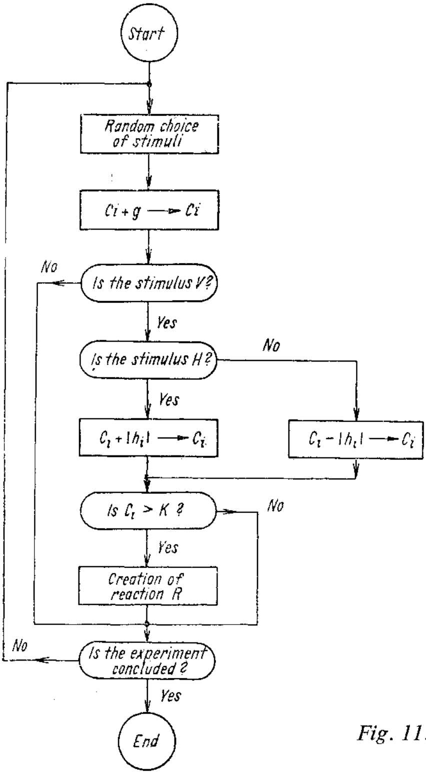

Fig. 11.4. Block diagram of algorithm modelling a conditioned reflex

v_j $(j = 1, 2, \ldots, t)$ via a variable conductance G_{ij}. Each of these conductances satisfies at all times the inequalities

$$0 \leqq G_{ij} \leqq G_{\max} . \tag{11.3}$$

The initial values of all conductances are zero, so that at the beginning there is no connection between the conductors.

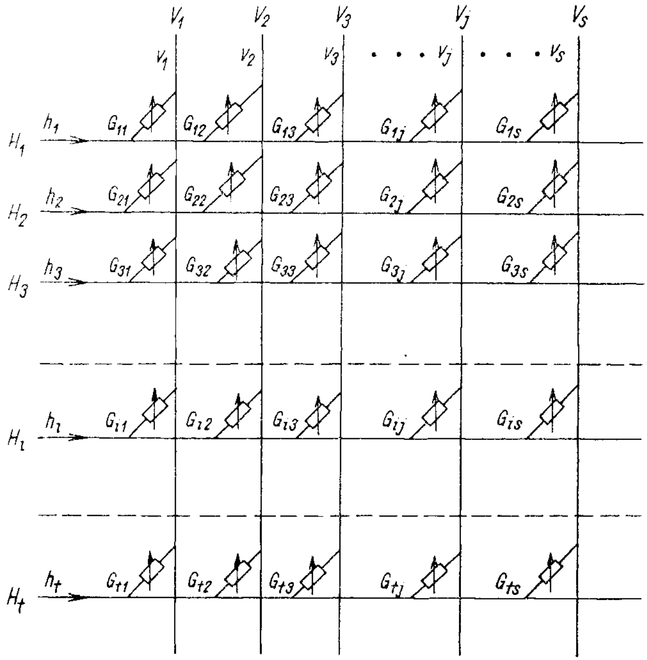

Fig. 11.5. Steinbuch conductivity matrix

The elementary signals $H_1, H_2, \ldots, H_s$ of the main stimuli are applied to the conductors $h_1, h_2, \ldots, h_s$, the signals $V_1, V_2, \ldots, V_t$ of the secondary stimuli being applied to the conductors $v_1, v_2, \ldots, v_t$. Both kinds of signal produce changes in the conductances G_{ij} within the limits defined by (11.3). The elementary signals H_i and V_j affect the conductance G_{ij} in accordance with the following table:

H_i	V_j	G_{ij}
0	0	does not change
0	1	decreases
1	0	does not change
1	1	increases

This table corresponds to the principle of the creation and extinction of an elementary conditioned reflex. The reflex is created when $G_{ij} = G_{max}$.

In the papers quoted, K. STEINBUCH shows that changes in the conductances G_{ij} can be realized in various manners, e.g. by means of electrochemical cells, ferrite cores, etc. He also shows that several matrices can be combined to make up larger systems, which can be used with success for modelling even very complicated behaviour patterns of the nervous system.

11.2 ABSTRACT MODELS OF NEURONS

The search for ever more perfect abstract models of neurons appears from the cybernetic point of view as a very important complement to experimental neurophysiological investigations. The model serves as a kind of explanation of the behaviour observed in neurons experimentally. However, some further properties usually follow from it. The verification or refutation of the existence of these properties in actual neurons is then the subject of further experimental work. If, on the contrary, the abstract model does not satisfy some of the facts discovered experimentally, it must be modified or replaced by a more satisfactory model.

Abstract models of neurons have undergone changes in accordance with progressively expanding neurophysiological knowledge. The first abstract model of the neuron was designed by the American neurophysiologist W. S. McCULLOCH in cooperation with the mathematician W. PITTS [B 47]. Their model distinguishes excitatory and inhibitory synapses only. It is assumed that an excitation can occur in a postsynaptic neuron if and only if

1. no inhibitory synapse has been excited,
2. the number of stimulated excitatory synapses is larger than or equal to a certain threshold value.

If we denote the number of stimulated excitatory synapses by the symbol e, the number of stimulated inhibitory synapses by the symbol i and the threshold value by the symbol p, the conditions for the creation

of an excitation in the neuron can be written down in the form of very simple relations:

$$\begin{aligned} i &= 0, \\ e &\geqq p. \end{aligned} \tag{11.4}$$

Another model was later designed by JOHN VON NEUMANN [B2]. In this model the neuron is excited if and only if the single inequality

$$e - i \geqq p \tag{11.5}$$

is satisfied.

A generalization of the two foregoing models is represented by the so-called *weight model*, in which a certain weight W_i $(i = 1, 2, \ldots)$ is assigned to each synapse, expressing the magnitude of the effect produced by the corresponding synapse upon the behaviour of the neuron. The states of the individual synapses can be expressed by two-valued Boolean

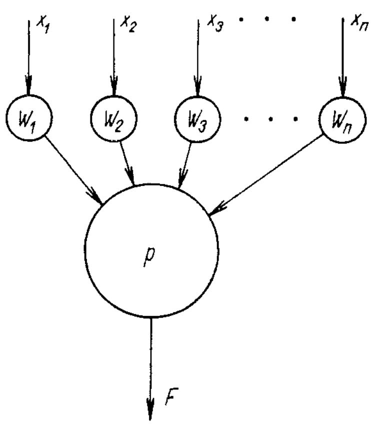

Fig. 11.6. Symbolic representation of the weight model of a neuron

variables x_i $(i = 1, 2, \ldots, n)$ in such a manner that the value $x_i = 1$ corresponds to the stimulated state of the i-th synapse and the value $x_i = 0$ to the opposite state of this synapse.

Assuming in general n synapses, whose state is expressed by the Boolean variables x_i $(i = 1, 2, \ldots, n)$, then the excitation of the neuron

(the output function F) will depend on the inequality

$$\sum_{i=1}^{n} x_i W_i \geqq p \tag{11.6}$$

being satisfied. The weight model will be symbolically designated as shown in Fig. 11.6.

Let us note that the weight model includes both the models mentioned previously. For, if we have $W_i = 1$ for the excitatory synapse and $W_i = -\infty$ (or -1 respectively) for the inhibitory synapse, we obtain the relation (11.4) (or (11.5), respectively). Moreover, the relation (11.6) offers an unlimited number of further possibilities as far as the choice of the weights W_i is concerned.

In his dissertation [B19], JÁN GECSEI introduces a still more general model which satisfies the most recent neurophysiological findings in a better manner. This model assumes that the excitation of the neuron depends not only upon the relation (11.6), but also on whether pairs, triplets or even higher groups of synapses are stimulated at the same time. Moreover, every group has its own weight. Thus, for three synapses ($n = 3$) we would obtain the following inequality in place of the relation (11.6):

$$x_1 W_1 + x_2 W_2 + x_3 W_3 + x_1 x_2 W_4 + x_1 x_3 W_5 + x_2 x_3 W_6 + x_1 x_2 x_3 W_7 \geqq p \,. \tag{11.7}$$

It appears that the behaviour of a model defined in this way is flexible to such an extent, that any Boolean function of n variables can be expressed by suitably choosing the weights W_i ($i = 1, 2, \ldots, n$) and the threshold p. This was not possible with the original weight model, expressed by the relation (11.6). J. GECSEI proves that for $n = 2$ the simple weight model is capable of expressing only fourteen (i.e. about 87%) out of the sixteen possible Boolean functions. With an increasing n the relative number of expressible functions decreases very rapidly (for $n = 3$, only 42% of all possible Boolean functions can be expressed, for $n = 4$ already only 3%), even though their absolute number increases.

By expanding the original weight model by further groups with their corresponding weights, the quoted number of realizable functions is

increased and it can be shown that a hypothetical neuron, which would contain all possible groups of variables (of which there are $2^n - 1$), would be capable of realizing – given a suitable choice of weights and threshold – all the possible Boolean functions, i.e. 100%.

In this connection it must by realized, of course, that in actual neurons there probably occur only some groups of synapses and it is thus evi-

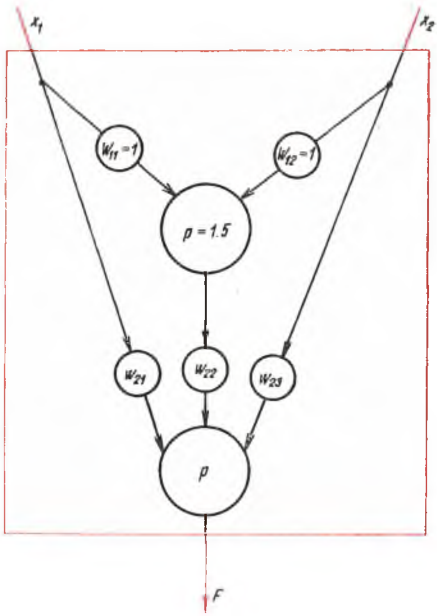

Fig. 11.7. Example of a combination of two weight models by means of which it is possible to realize all Boolean functions of two variables

dently impossible for each neuron to realize all the possible Boolean functions. A simple reflection will show, however, that the limited possibilities of individual neurons can be expanded at will by connecting several neurons in a simple network. Thus, for instance, for two variables we can achieve the realization of all sixteen Boolean functions by connecting two simple weight models of neurons in the manner shown in Fig. 11.7.

Of course, we must also remember that the capacity of expressing Boolean functions is certainly not the only measure of the perfection of a nervous system.

Another way of expanding the preceding model according to [B19] consists in considering the actual waveforms of stimuli and responses in the form of sequences of short impulses of approximately the same shape, the frequency of which is proportional to the intensity of stimulation. It appears that a neuron, whose behaviour shows a substantially logical character (see Chapter 8) is thus capable of transmitting even quantitative data. Using statistical methods, the effects of mutually uncorrelated sequences of input pulses can also be considered.

A very important problem associated with the study of the nervous system is the problem of learning. It is of interest to note that the capability to learn can be observed already at the level of a single neuron. Learning is here considered to mean such changes in the values of weights and threshold – occurring in dependence upon the sequence of prior stimuli – as a result of which the neuron is more sensitive to stimuli such as those already received previously. The neuron thus acquires the capability to (or learns to) distinguish stimuli received more frequently from less frequent ones. For this purpose the neuron is equipped with its own algorithm for changing weights and threshold. Let us now illustrate this possibility on a very simple example.

Let us assume, for instance, a neuron with three input variables x_1, x_2 and x_3, and consider the following algorithm: At the start we have $W_i = 0$ for all values of i. Every signal for which $x_i = 1$ increases the corresponding weight W_i by unity, whereas every signal for which $x_i = 0$ reduces this weight by unity.

If a neuron which obeys this algorithm receives the sequence

x_3	x_2	x_1
1	1	1
1	1	0
0	1	1

then the weights will have the values $W_1 = 1$, $W_2 = 3$ and $W_3 = 1$ respectively. It is possible to ascertain that, with a suitable choice of the

threshold (e.g. $p = 3{\cdot}5$), a neuron with the weights quoted will be excitable only by the combinations listed above, i.e. only by combinations equal to those received previously.

It is also possible to consider changes in other parameters (e.g. in the refractory period, in the synaptic memory, etc.), which greatly increase the flexibility of the model. It is an important task of contemporary neurophysiology to verify the truth of these hypotheses and to enrich the possibilities of cybernetic modelling by further experimental facts.

11.3 Engineering Models of Neurons

Abstract models of neurons have, as shown in the foregoing section, a predominantly epistemological significance. We therefore endeavour to make these models as expressive of the behaviour of neurons as possible, with all their advantages and insufficiences.

The situation is different in the case of engineering models of neurons, which form the subject of interest to bionics. In this case the neuron

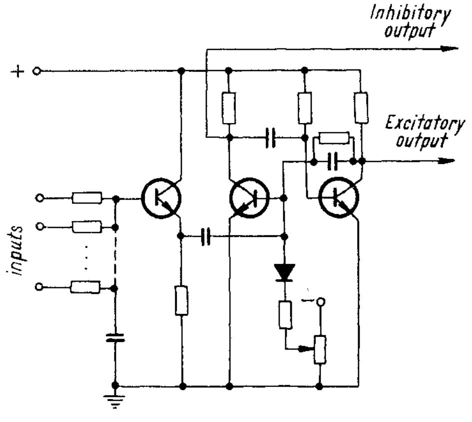

Fig. 11.8. Engineering model of neuron

serves by its characteristic behaviour as a pattern for engineering devices. In this respect, it is not our purpose to model all properties of the neuron, but only those which – for some reason – appear technically advan-

Part Three

SOME STUDIES
IN CYBERNETIC MODELLING

CHAPTER 12

HIGHER TYPES OF SYSTEM BEHAVIOUR

12.1 THE APPLICATION OF PSYCHOLOGICAL CONCEPTS TO ANIMATE AND INANIMATE SYSTEMS

If we want to describe the behaviour of human beings in various complicated situations, we use expressions portraying them in different moods, states, intentions, static and dynamic circumstances, e.g.:

1. "*He enthusiastically grappled with all obstacles in his way*", or

2. "*He drew upon wide experience acquired under similar circumstances*", or

3. "*He understood immediately* what it was all about".

Such descriptions are very well suited to express human behaviour. Without them we would find it very hard to put into words how this or the other person behaves, and make ourselves understood.

Since inanimate systems are acquiring ever more complicated patterns of behaviour, a description of their behaviour necessarily demands the use of similar concepts, i.e. similar designations of their states, situations, their complicated behaviour under different circumstances, their manner of reacting to external or internal stimuli, etc.

To avoid the introduction of new and different concepts in cases where the behaviour of inanimate systems closely resembles that of living systems, it is desirable to introduce common designations. Conversely, care must be taken to shun them whenever they are unsuitable. The use of psychological concepts common to the behaviour of both animate and inanimate systems must therefore be based on the most accurate definitions, starting with psychological concepts in animate systems and physical concepts in inanimate systems. We must not content ourselves with an intuitive or even only subjective comparison of the two types of system. The definitions of various kinds of behaviour must thus be based on a well-founded study of the animate and inanimate world, and such

definitions can be arrived at only on the basis of very close interdisciplinary co-operation.

To illustrate the difficulty of the problems involved, let us put the following questions, using the examples presented above:

1. What will be the behaviour of a machine of which we shall be able to say that it "*enthusiastically grapples with all obstacles in its way*"? What is the meaning of the word "*enthusiastically*" in connection with the behaviour of the machine? What do we mean by "*obstacles*" to the work of the machine?

2. When shall we be entitled to say that "*the machine draws on wide experience*"? And what do we mean by "*similar circumstances*"? How is the machine to recognize that it does something "*under similar circumstances*", so that it can acquire "*wide experience*"?

3. When shall we be able to say that a machine or some other inanimate system "*understands what it is all about*", or at least to find an adequate substitute for the concept of "*understanding*", by which we designate a highly developed type of behaviour in man, and from which point onwards shall we be entitled to use it in connection with the behaviour of a machine?

A whole series of similar difficulties is encountered when trying to apply practically any psychological description to an inanimate system.

On the other hand, we must face this problem if we want to use man as a pattern for the design of ever more perfect inanimate systems. For it is just these concepts that help us not only to describe, but sometimes even to vindicate the behaviour and decisions of man in certain situations. Decision-making, which we would very much like to simulate by machines, cannot de bescribed or justified without using psychological concepts. This is exemplified by the case when a chess-player explains that he decided in a given situation to make just this move and no other because it was the best according to his experience. What, in this case, is "*his experience*" and how would we have to design a machine that would also be capable of "*acquiring experience*"? In some other instance, when asked why he got up from his books and stopped learning, a student might answer "*It is my impression that I know enough*". What is the

meaning of "*to get an impression*", and when shall we be able to say of a machine that "*it has got an impression*", so as to be able in a "*similar*" situation to induce in the machine a behaviour "*similar*" to that of the student?

And, finally, what must happen in a machine so as to make it correctly react to the instruction, given in the following verbal form: "*Read a part of this text, compare it with the text read previously, and go on reading as soon as you have understood the necessary relations*"? This is how we talk one with the other, man to man, in concepts that are quite clear to us. We are quite helpless, however, if we have to (or want to) apply them to a machine, either in a verbal or in an otherwise modified form.

12.2 Decision-making

In living systems, decision-making is designated as a process that occurs in case the system has, at a given instant, several courses of action open to it. Since only a single course can be selected at any given time, it must be decided which of the possible courses is to be taken. The course of action to be taken can be chosen in different ways, the characteristic methods being:

1. *Random choice,*
2. *Choice according to the actual state,*
3. *Combined choice, using the first two methods.*

For a long time, nothing resembling a decision-making process could be observed to exist in the inanimate world. With the advent of digital computers, however, it appeared that such a machine cannot even be made ready for operation in an economic manner, unless procedures very similar to decision-making are applied. We have therefore started using – without much hesitation – the concepts of decision-making as well as decision-making processes in connection with digital computers. Hence, the use of these terms has been transferred from here to other processes taking place in the inanimate world.

12.3 Decision-making by Random Choice of Sequel

In computers, *random choice* is accomplished by inserting, for instance, a table of random numbers. At the same time rules must be inserted in accordance with which the random numbers, selected as required, one following the other, are used to choose the desired procedure.

As an example, let us present a situation where the computer has to decide randomly upon the first move in a game of draughts. At the beginning of the game there are only four pieces that can be moved: three of them in two different manners, the fourth piece in a single manner. I.e., there are seven possible moves. Let us denote these seven moves by different numbers, e.g. 1 to 7. We have thus assigned a decimal figure to every possible course of action. Let us then establish the following rules for the use of the table of random numbers:

a) Find the first number in the table of random numbers.

b) Pick out the first digit of this number. If this is one of the digits from 1 to 7, choose the move designated by this digit.

c) If the first digit is not among the digits from 1 to 7, take the following number from the table of random numbers and proceed as before, etc.

d) If we start another game later, or whenever we need our table later in the course of the game, we always use the next number in the table that has not yet been used since the beginning of the game.

As can be seen from this example, the application of the random choice consists of two steps: the designation of the possible courses of action, and the choice by a random process. Besides a table, other methods can also be used to generate a random process in a computer. According to statistical investigations random numbers can be produced, for instance, by raising numbers to the second power, taking the two middle digits of the result, raising these again to the second power, etc. The sequence of numbers obtained in this way may be considered – within a limited interval – as random. Similar procedures are suited especially to computers containing an arithmetic unit capable of multiplication. However, random processes can be generated in computers by a number of other methods also.

12.4 DECISION-MAKING ACCORDING TO THE ACTUAL STATE

Living systems frequently make *decisions according to how a situation develops at a given instant.* We say, for instance: If it is nice on Sunday, we shall go for a walk; otherwise we shall stay at home. We have thus 1. fixed the time when we are going to make a particular decision, 2. determined the conditions on which our decision will be based, 3. assigned a single course of action to every condition (often to sets of conditions).

We very frequently encounter quite similar situations when devising programs for digital computers. Let us imagine that we want to compute the passage of a ray of light through an optical system, e.g. a telescope. When, during its passage through the body tube, the ray impinges upon the glass surface of a lens it is refracted, i.e. it changes its direction. Since the optical system of a telescope has many boundary surfaces of this kind, the ray changes its direction many times. If the ray enters the telescope at some angle, we do not know in advance where it will emerge. However, not every ray will pass through the whole system. It may happen that, as the result of a change in direction, it will impinge somewhere upon the wall of the tube. In such a case the ray is absorbed by the wall and does not emerge at the end of the body tube.

When computing the optical system we must ascertain where all the rays that entered the system will emerge from the tube. If in the course of our computation we find that some ray impinges on the wall, it would be useless to go on computing its path.

Two different situation can thus arise in the course of the computation considered above. The first situation occurs when the ray remains throughout its passage inside the tube. In this case the computer goes on computing its path. The second situation arises when the ray is deflected towards the wall of the tube. In this case the computation of its path should be stopped and the computer should start computing the path of another ray entering the optical system. Finally, it should be stated when to ascertain whether the ray remains inside the tube or is absorbed by the wall, i.e. when decisions are to be made. At certain steps in the program a check is inserted which shows whether the situation at the chosen instant corresponds to the first or to the second eventuality.

In our case this check could be performed, for instance, by inserting a calculation of the distance between a suitable point of the optical path and the axis of the tube. If this distance is smaller than the tube radius, we are concerned with the first case when the ray is still inside the tube. If the distance is larger than the radius, the ray would be outside the tube wall.

Let us take a closer look at this situation. Let d be the difference found by the computer between the distance of the selected point in the path from the tube axis t and the tube radius r, i.e.

$$t - r = \mathrm{d}.$$

The sign of d shows which eventuality we are concerned with. If d is negative, the ray is still inside the tube, if d is positive, the ray had been deflected to the tube wall. We must insert an additional convention in the computer together with the program stating that, when $d = 0$, the computer should proceed as though d were positive.

Let us now compare our situation with the three points presented at the beginning of this section. To compute our optical system, we have determined the following:

1. The course of the computation will be decided upon after computing the number d.
2. We have laid down that the decision will be made according to the sign of the number d.
3. We have assigned a particular course of action to each of the two possibilities.

Decision-making performed in this manner is prepared in advance and depends on certain conditions. In the technical world these conditions are called *decision criteria*.

Thus, if some process taking place in the inanimate world can be described by the three points quoted above, we speak of decision-making and, moreover, introduce a new concept – that of decision criteria. Hence, in return, the term "decision criteria" is introduced in the description of decision-making in living systems to describe the conditions on which the decision is based in the given case.

12.5 Combined Decision-making

Both in living and in inanimate systems, decisions are frequently arrived at by a combination of the two foregoing methods. If, for some reason, the prepared decision criteria are inaccessible or cannot be applied to a particular situation, and it is still necessary to decide between several possible courses of action, we first use the random method. Another advantageous combination consists in deciding between whole groups of possible courses of action, e.g. on the basis of considerations concerning courses of action that are of advantage from some particular point of view. If some of the courses of action appear to be equally advantageous and there is none better than these, a random decision is made between them. This is a method used very frequently in situations that occur often in so-called strategic games, such as draughts, chess, go, bridge, etc. When speaking of man we say that he decides on the basis of considerations; machines are said to create a basis for their decision by processing the pertinent data.

In man, decision criteria are not always known to a sufficient extent. According to expert opinion, considerations used as a basis for decision-making – if not founded on scientific deductions, on the strict use of logic, etc. – are strongly influenced by an emotional component. On the other hand, in machines the process of decision-making must be based on a program, even though the latter may utilize random processes. It is worth while to dwell for a moment on the following two examples.

The first of these is the case where a random process was used for decision-making. In such instances it is impossible a) to know in advance how the machine will continue in a particular situation, b) to reproduce such a process, even though it takes place in a machine, since, when arriving at the appropriate point for a second time, a random decision would have to follow again. If this decision would be reproducible intentionally (i.e. not based on chance), it would no longer be random.

We are thus concerned with machine behaviour that is unforeseeable or intentionally unreproducible from the point of view of possible sequels. Even when starting from the same initial conditions, the machine may arrive at different results. To describe such processes, even

when they take place in a machine, we must use the statistical aspect. I.e., we can no longer speak of the course of action that will be taken, but only of the probability with which one or the other course will be selected. This aspect is acquiring increasing importance in the description of machine behaviour.

The second case is exemplified by the situation when we enable the machine to change its decision criteria in dependence upon the results achieved, responses obtained from its environment, etc. Here we confine ourselves to the observation that in such cases we approach situations in which we speak, in connection with living systems, of the acquisition of experience, the perfection of behaviour, learning, acquiring a feeling for certain situations, etc. Similar cases will be treated in greater detail in the following sections.

12.6 Experience

We acquire experience consciously as well as subconsciously. Experience enables us to foresee what some particular decision of ours will lead to – i.e. something we could not have assessed before we accumulated our experience. Improvement of behaviour based on experience is remarkable in that the manner in which experience can or cannot be acquired is not determined in advance. The acquisition of experience is a broad epistemological process that adapts itself to the most varied perceptions, phenomena, events and circumstances. It is a method by which we improve under certain circumstances our behaviour so that our initial groping changes through experience into some sort of certainty of behaviour.

The acquisition of experience is a very attractive process when applied to inanimate systems. Its insertion in the operation of a machine means that we enable the machine to adapt itself purposefully to new situations. In cases when its decision-making was initially random or unsupported by experience, decision-making based on experience develops in the machine, frequently leading directly to the desired goal. At the present we witness many inanimate systems being endowed with the facility of acquiring experience, no matter whether we are concerned with machines

playing strategic games, or with inanimate models of the higher types of behaviour in living systems.

So as to be able to describe what process in an inanimate system can be designated as the acquisition of experience, we must first describe what this process looks like in a living system. At the same time we shall take notice of the characteristic signs of this process, which will be subsequently used in our description of the acquisition of experience by inanimate systems.

12.7 The Acquisition of Experience by Living Systems

Let us describe with the aid of examples, how experience develops in a living system. Let us assume that we are in unfamiliar surroundings, e.g. in a large hospital which we will have to visit several times during the next few days. We walk along a corridor and try to open the first door. Sometimes we find it locked, sometimes unlocked. In this manner we make several attempts the results of which – i.e. whether the door is locked or not – are not known in advance. After some tests of this kind we discover a lamp above the door which is lit when the door is unlocked, and switched off when the door is locked. We therefore begin to assume that there exists some relation between the lighting of the lamp on the one hand and the locking of the door on the other. We verify this relationship by some further tests. Our behaviour will change from the moment in which we decide that the relation observed corresponds to reality. We say that we have gained experience which will reveal itself in that the next time we shall not try to open the door immediately, but shall first take a look at the lamp. According to the state of the lamp we shall presume whether the door is locked or not. If the lamp is lit, we shall know that the door is unlocked, if it is dark, we shall know that the door is locked. The experience thus acquired enables us to dispense with experiments the result of which is not known, i.e. with random experiments, and offers a basis for direct decision-making. If the lamp is lit, we know that we can enter through the door; if it is unlit, we know in advance that it would be in vain to attempt opening the door.

Now let us describe this process by different, more general, words. In the first phase we performed many experiments. In their course we noticed (consciously or subconsciously) certain relations between the results of individual experiments (door locked or unlocked) and some phenomenon in our environment (e.g. the lit or dark lamp above the door, a clean or dirty floor, the lighting of the corridor, the hour at which we tried to open the door, etc.). After a certain number of experiments we discovered, which of the phenomena in our environment was related to the results of the experiments. At the same time we found the nature of this relationship (the lighted lamp corresponds to the unlocked door, the dark lamp to the locked door, and not vice versa). Based on this discovery we have changed our behaviour in that we now act in accordance with the relationship ascertained. The state of the lamp is a decision criterion which tells us how to act in order to avoid further unnecessary experiments.

12.8 General Description of Experience as a Process

On the basis of the foregoing explanation, we can describe the acquisition of experience as a process proceeding in three phases:

1. *experimentation, with the simultaneous observation of arbitrary attendant phenomena,*
2. *determination of the relationship between the results of the experiments performed and the phenomena observed,*
3. *change of behaviour, based on the relationship discovered.*

These three phases are used to facilitate the description of the process under investigation. In actual fact these phases may overlap, or sometimes take place simultaneously. This will be seen to happen not only with living systems, e.g. when we modify our previous experience, verify it by further material or adjust it according to newly obtained results, but also with inanimate systems.

The system which will be supposed to be acquiring experience, will be denoted in the following section by the symbol **Z**.

12.9 Experimentation Combined with the Simultaneous Observation of Further Phenomena

In the first phase, system $\boldsymbol{Z}$ accumulates experimental material as well as material concerning the state of its environment. This accumulation can proceed so that the system is directly ordered to collect material for the given purpose. In inanimate systems this is done, for instance, by the inserted program. As examples we quote a digital computer programmed to play draughts by the method of acquiring experience, or a computer designed to control a complex metallurgical process whose method of control is not yet known sufficiently well. The method of accumulating experimental material for the purpose of accumulating and deriving experience, as prepared in the program of a computer, resembles the conscious performance of experiments and the remembering of their results in living systems. This is true in the sense that this is done in both cases with the aim of finally obtaining, by processing this material, a basis for further useful decision-making which could not be realized without the accumulation and evaluation of experiential material.

In some cases, however, we witness situations developing in a different manner. Physicians know very well that in case histories, containing anamneses, diagnoses and the results of various examinations, the most diverse data and relations are systematically accumulated without anybody having determined in advance what is to happen with the material thus accumulated, and how it will be utilized to some greater extent in the future. In a similar manner, the most diverse data are accumulated on metallurgical processes by filling in so-called heat records. We might find many other instances when experimental material (i.e. data on repeatedly occurring short-time processes, whose progress and result is not known for certain in advance) is accumulated without anybody having said beforehand what this material will be used for.

Let us remind ourselves, that such material is accumulated for us by our memory. We remember various situations, states, phenomena, etc., without always realizing in advance what will be the good of it. In many cases we remember experience or stimuli that did not even pass through our consciousness. Material is accumulated in this case without

a given purpose, or for a purpose other than a subsequent evaluation in the form of experience. Considering that the material acquired is not originally intended for later evaluation, such a process which may take place, for instance, in a computer automatically checking the stock of a large warehouse, the fluctuation of production costs, etc., resembles the first phase of the subconscious collection of experience in a living system. Not, of course, in the sense of consciousness in the machine and the living system, but in the sense of the aim for which this material is accumulated, i.e. in a sense to which we shall return when going through the further phases.

As far as the simultaneous observation of attendant phenomena is concerned, we must remember that it is in the very nature of experience that we do not know in advance what the results of the experiment will be related to. When collecting material we must therefore pay attention to all the simultaneously accessible phenomena in order to profit from the experiments as much as possible. That is why – adhering to the examples quoted above – case histories include as many data as possible, and why the greatest possible number of seemingly unrelated data are entered in heat records. In living systems, the greatest part is played in this respect by the memory, which automatically retains far more than we would consider as useful, if we were to decide on every individual item whether to remember it or not.

12.10 Determination of the Relations between the Results of Experiments and the Attendant Phenomena

The second phase in the acquisition of experience is a process that has been very well described in mathematics. This is the statistical process of determining relations between the results of experiments and the accompanying phenomena. It is of interest to note that the determination of these relationships proceeds in living systems automatically, frequently without any apparent effort on the part of the living system concerned, whereas the determination of relationships in statistics is a very toilsome matter. On the other hand we must remember that, as a rule, the relationships found in living systems are simple,

whereas mathematics often disclose relationships that are otherwise unperceivable. (By the way, but for the sake of completeness, we should also realize that observation and direct evaluation are not the only means on which living systems depend for the acquisition of their knowledge).

These problems are dealt with theoretically by statistics, which permits relationships to be evalutated with regard to the probability of the given relation being valid or not. In less frequent cases, when the experimental material yields an unambiguous relation, statistical means need not be used for its description. This is the case with simple experiments, the results of which are not distorted by further unobserved phenomena.

Methods for determining relationships are widely described in technical literature*). This is a phase that can very well proceed in machines. The types of computation involved have very frequently been performed by computers long before anybody started to investigate the acquisition of experience by inanimate systems.

These computations will eliminate phenomena unrelated to the given task and will find those where such relations may be considered. In cases where the relationship is evident, the computations will also determine what this relationship consists in, expressing it, as required, in tabular, algebraic, or some other suitable form.

12.11 CHANGES IN BEHAVIOUR BASED ON DISCOVERED RELATIONSHIPS

If a system $\boldsymbol{Z}$ accumulates a sufficient amount of material and evaluates it, changes in its behaviour may take place in that it will henceforth "answer the questions posed" directly according to the relations determined. In living systems this will reveal itself by the fact that the system will stop performing experiments and will submit its decisions to the relations found. In system $\boldsymbol{Z}$ this will reveal itself in that the system will stop collecting material and will now correctly and in accordance with the ascertained relationships react to stimuli received from without, to which it previously did not have any reaction prepared.

*) E.g. in Ref. [B73], which introduces a method suitable for discrete processes.

The discovered relationship, on the basis of which the system $\boldsymbol{Z}$ will henceforth react, may be spoken of as knowledge accumulated through experience. If system $\boldsymbol{Z}$ collects experimental material (even though according to a given program), evaluates it on its own and changes its own behaviour, experience obtained in this manner will be termed the proper experience of system $\boldsymbol{Z}$. The given program, which determines what kind of material is to be collected, no matter whether experimental or observational, is then regarded as a stimulus to acquire experience. The fact that the stimulus may originate outside the system $\boldsymbol{Z}$ is no obstacle to our considering the experience thus acquired as proper experience.

12.12 THE USE OF EXPERIENCE BY THE SYSTEM AND ITS JUSTIFICATION

The acquisition of experience is a process that need not necessarily lead to an agreement with reality. In this process we nowhere examine the properties of the accumulated experimental material, nor those of the phenomena observed at the same time. It may therefore easily happen that the relationship discovered is not correct. This may happen either by chance or, for instance, because the experimental material has been collected with a bias, the phenomena observed have not been sufficiently discriminated, etc. In the acquisition of experience we may thus arrive at incorrect conclusions, in other words we may find relations that do not exist in reality.

This difficulty lies directly in the nature of the experiential process and it cannot be eliminated except by a verification of the results, i.e. by a higher form of experience.

At this moment we must realize another very important aspect of experience, namely its subjective character. A system that acquires experience without verifying it, behaves in accordance with it without regard to whether this experience is correct or not. This can be seen to happen in living systems in case when there is no verification of experience, which is part of a process superior to the acquisition of experience. This, however, will also be witnessed in inanimate systems that operate with experiential processes.

As will be seen in the *model of the self-preservative instinct* described by A. SVOBODA*), it is possible to prepare in inanimate systems a process whereby the older experience transferred to a new situation is abandoned and adapted to the new situation.

Here we should like to remind the reader, that experience is a process that takes place in accordance with certain laws which we have already described. However, the behaviour of a system according to a certain relationship need not always be the result of an experiential process. Into a machine we can, with the aid of a program, directly insert the relationships according to which the machine is to behave. In a similar manner, the knowledge of certain relationships can be introduced into a living system without the latter having had to acquire experience. When concerned with human beings, we speak in such cases of having imparted our knowledge to some other person. In case we have acquired our knowledge by experience, we speak of having communicated our experience.

Thus, we do not speak of experience according to the results achieved, but according to the manner in which these results have been obtained.

12.13 GOAL-SEEKING BEHAVIOUR

We are used to speak of *goal-seaking behaviour,* as a rule, in rather complicated living systems only. This term has been transferred, however, from living to inanimate systems where it is used in cases where a process taking place in the inanimate world aims at achieving a state determined in advance, or a certain stage here also called a goal.

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*) The model of the self-preservative instinct, introduced by A. SVOBODA in Ref. [B72] and later elaborated by P. PELIKÁN — see Ref. [B52] — consists of a mobile digital computer which records its own fault incidence at different locations of its "living space". It decides its direction of movement randomly, the probability of the choice of any particular direction being inversely proportional to its fault incidence at the corresponding spot in its environment. The latest information concerning the fault incidence has the greatest effect, the oldest information exercises the least effect.

Goal-seeking behaviour is of great importance to the observation and comparison of behaviour in living and inanimate systems, since all around us we encounter many processes that admit of observation from just this point of view. Goal-seeking behaviour is so frequent in both living and inanimate systems, that many authors regard it as the basis of the behaviour of systems that are of interest to cybernetics, and they have therefore attempted to incorporate goal-seeking behaviour also in the definition of cybernetics.

Goal-seeking behaviour as a process taking place in a system in cooperation with its environment has several characteristic traits. In order to be able to speak of goal-seeking behaviour, the following must be given:

1. System **S**, which features goal-seeking behaviour.
2. A goal towards which the system is directed by its behaviour.
3. A control element which directs the system towards its goal.
4. A representation of the goal in the control element.
5. Disturbing effects which hinder system **S** from attaining its goal.
6. A connection between the goal and the control element of system **S**.

These features are found in goal-seeking processes both in living and inanimate systems. An example of goal-seeking behaviour in living systems can be observed in a cat which has smelt a mouse. Its behaviour, that has so far been indifferent, becomes goal-seaking. System **S** is exemplified by the cat, the goal towards which it aims is the capture of the mouse. The control element is the nervous system of the cat, in particular its brain. The goal is represented in the memory and imagination of the cat. This has been evoked by the odour perceived by the cat. The disturbing effects are represented by the evasive movements of the mouse which, from a certain moment onwards, will try to escape the cat. The connection between the goal and the control element will first be represented by the odour of the mouse, later by the fact that the cat sees the mouse.

An example of an inanimate system possessing goal-seeking behaviour is the automatic system of anti-aircraft defence. The goal consists in shooting down the enemy aircraft. The control element is the anti-aircraft predictor which derives the firing data from the automatically

ascertained aircraft position. The system is connected with its goal by light rays in the case of optical direction finding, by centrimetric waves when radar is used.

12.14 The Goal

The goal is defined by the state into which we want to get the system under investigation. The goal must be known in advance and designated as such. A process in which we do not know in advance which state is regarded as the goal, or at least the road leading to the goal, cannot be spoken of as goal-seeking behaviour.

In various processes the goal may be defined in very diverse manners. We should realize what kind of process can be regarded as goal-seeking behaviour and notice how the goal is defined.

When a ship sails to a port or a tourist wanders to a place determined in advance, a process of goal-seeking behaviour is evolved. In such a case this means the attainment of an immovable goal defined, for instance, by its geographical position. The connection between the ship and its goal is taken care of by stars, a compass, or some other device that enables the captain to ascertain whether he is nearing his goal or is increasing his distance from it. In a similar manner a tourist utilizes landmarks, maps, or other means to make sure of the position of his goal and to find whether he is approaching it or not. In such cases it is quite exceptional to lose the knowledge of the goal or of the direction towards it.

A control system can also be regarded as a system with goal-seeking behaviour. The peculiarity of such a system consists in that its goal is usually defined as a certain equilibrial state. If the system is deflected from its equilibrial state by some disturbing effect, the regulator which controls the system must take steps to renew equilibrium. Another peculiarity is that the goal is not directly represented in advance in the control device. At the moment when it is not in equilibrium, the system does not "know" its goal. However, it incorporates rules of how to attain that goal. This is a situation similar to that in which a tourist would find himself if he were not told his goal, but would only obtain accurate instructions leading him from one cross-roads to the other: "At the first cross-roads, marked by a yellow signpost, you will take the first road to

the right. After walking for a hundred yards, you will turn right again, etc.". Although the tourist will not know his goal, he will attain it by knowing the road leading to it. An observer who follows the tourist will regard his behaviour as goal-seeking. If the observer is in touch with the man who instructs the tourist, he will even know this goal and the behaviour of the tourist will appear to him as a conscious effort to attain the goal. When assessing the goal-seeking behaviour of a system, the knowledge of the goal may thus be replaced by a knowledge of the road leading to it, even though the goal itself might be unknown to the corresponding system.

Processes involving the accomplishment of a given task, the solution of a distinct problem, the search for an answer to a given question, and many similar processes are also considered as goal-seeking behaviour. Nature has endowed man with the faculty to follow many goals at the same time. We often prepare a program for this afternoon, for tomorrow, for a week in advance, all that without having to leave out a single point of our programs.

A very interesting type of goal-seeking behaviour, from which cybernetics is perpetually profiting, is the behaviour of man when playing some strategic game, e.g. chess, draughts, go, bridge, etc. From the viewpoint of goal-seeking behaviour these processes are peculiar in that the goal is known, but not the road leading to it. In the course of the game, the given goal provides no direct orientation. It is difficult and sometimes impossible to assess whether the player is approaching his goal or not. The final goal – the winning of the game – must in the course of the game be substituted by many auxiliary goals, such as gaining an advantage over one's opponent, obtaining a more advantageous position, preparing a trap, etc. During the game the player can only presume that he is approaching his goal, but he has no means of making sure. If a player speaks, during the game, of winning, he says as a rule that he has a greater chance of winning than a while ago, that he has improved or deteriorated his position, etc. In the sense that the road to the given goal is unknown, goal-seeking behaviour in strategic games greatly resembles our endeavour to solve some scientific problem, and is also similar to so-called creative activities including the creation of works of art.

12.15 Hypothesis as an Auxiliary Goal

From the point of view of goal-seeking behaviour, *a hypothesis* is an auxiliary substitutive goal which for a certain time replaces the final goal. Hypotheses are frequently used in the world of science as a guide to further work. In the preceding section we have shown that the player of a strategic game also sets himself auxiliary goals. An interesting problem, whose solution opens the road to the use of working methods employing hypotheses in inanimate systems, is the question of whence to take appropriate stimuli and how to utilize them in the formulation of a suitable hypothesis.

Regarded from the viewpoint of goal-seeking behaviour, this question is closely related to the question of where an inanimate system is to take stimuli enabling it to establish an auxiliary goal at the appropriate moment on its road to the solution of a given problem, and secondly, of how to establish this auxiliary goal so as to bring the system nearer to its final goal. Such questions crop up quite concretely, for instance, when attempting to set up a program for a digital computer intended to play chess.

It is worth while noting some points which, although we are going to present them in connection with chess-playing, have a close general relation to the problems just mentioned. If a chess-player is to play his game at a higher level, he must have a well-tried strategy as well as well-tried tactics all ready prepared in his mind. It is of no importance how he acquired his strategy and tactics, whether by experience, study, conversation, or otherwise. A strategy enables the player to set up in advance auxiliary goals, called strategic goals. Since not even the road to a strategic goal is given unequivocally, the player sets himself tactical goals, i.e. still closer goals by means of which he tries step by step to approach the nearest strategic goal.

The strategy and tactics of a player thus form a set of rules which he brings with himself into the game. With the aid of these rules he then tries to establish auxiliary goals. In chess manuals dealing, for instance, with the middle game, we will find many theorems explaining the so-called strategy. Essentially, we are concerned with instructions saying what is to be achieved in this or the other situation. These instructions

declare, for instance, that an empty column should be covered by one's own rook before the opponent does so or that, after a certain opening, it is advantageous to wait with one's own castling until after the opponent has castled. At other times it is said that it is of advantage to obtain a superiority of pieces on the queen's wing, to reduce the freedom of movement of the opponent's pieces, to concentrate pressure at a certain place, etc. All such rules and theorems, instructions and advice are most frequently used to enable the player to establish a particular goal closer than the final goal, which is checkmate to the opponent. We are thus concerned with correctly putting together a strategic plan in the course of the process, the important thing being that the pertinent rules must be known beforehand. Strategic and tactical goals cannot be set up without a knowledge of the principles of strategy and tactics. Strategic and tactical rules, if not acquired by learning, can be acquired by experience, which in principle consists of the accumulation of knowledge concerning the superiority of certain steps, actions and decisions.

Considering such hypotheses from the viewpoint of what has been said of auxiliary goals, it will be found that a hypothesis playing the part of an auxiliary goal can only be established on the basis of rules given in advance, which we call strategic rules. If these rules are not known, the hypothesis must be built up on the basis of experience. That is, we must first perform a number of random experiments in the field under investigation, and gain experience by their evaluation. The knowledge accumulated by experience can then be used (in simple cases directly) to establish the corresponding hypothesis.

CHAPTER 13

PROPER MODEL AND INFORMATION

13.1 INFORMATION AS CODED COMMUNICATION

The word *information* is used, in its current sense, very often to express the fact that we have communicated something to some other person. So as to be able to speak clearly and satisfactorily of this theme, let us first introduce the necessary terms. As a rule, the communication of information is regarded as an action whereby somebody informs somebody else of something. We are thus concerned with an interaction of three systems, designated as follows:

the *informing system*, called system **A**,

the *system* that is being *informed*, called system **B**,

and the *system on which information is given*, called system **C**.

The situation is then as follows. System **A**, in order to be able to convey to system **B** some information on system **C**, must first of all somewhere contain this information. System **A** is thus assumed to have been in such contact with system **C**, that it is now able to give information on it. Let us assume the contact between system **A** and system **C** to have been direct, i.e. without the mediation of some other system that would be essential to our consideration from the viewpoint of the situation described. Such direct contact may have consisted, for instance, in system **A** having kept system **C** under observation, or system **C** having transmitted some signals which were picked up by system **A**. The signals transmitted by system **C** and received by system **A** may have been either retained by system **A**, or processed by it in some manner, e.g. combined with other signals stored in it previously, or transformed according to some rules, etc. Signals obtained, processed and retained in this manner serve for system **A** as the basis for conveying information on system **C**.

System **A** thus plays the part of a system which mediates the contact between system **B** and system **C**. The information on system **C** thus received by system **B** is not obtained by direct contact with system **C**. In various cases this information may therefore be in some manner distorted, processed, etc. System **A** thus appears in this situation as a system mediating the interaction between system **B** and system **C**.

Fig. 13.1 depicts the simplest possible case of conveying information. System **A** receives signals from **C** and passes them to system **B**. Fig. 13.2 shows a situation where system **A** is in two-way communication both

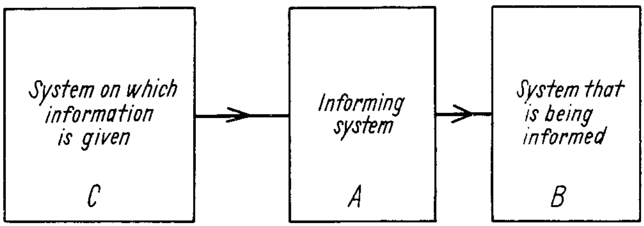

Fig. 13.1. Simplest case of conveying information. The informing system, **A**, *appears here as a system which mediates the informational contact of system* **B** *with system* **C**

with system **C** and system **B**. It should be noted that in case **A** is the system informing system **B**, there is no direct path between **C** and **B**.

Now, why does an informational interaction actually occur between such systems? Why does system **B** not obtain the required information directly from system **C**? The answer is very simple. For some reason, system **B** cannot get into direct touch with system **C**. This is why it must use the intermediary system **A** in order to get signals from **C**. Let us only remember situations that occur very frequently in our own life. We want to know, for instance, what the Bulgarian coast of the Black Sea looks like, without ever having been there and without having the chance of getting there. The only possibility is to ask some acquaintance who has been there, or to take a look at a picture of this coast. In this case the Black Sea coast is the system **C** with which we, as system **B**, come into contact only through the mediation of somebody who has been there, or through the mediation of a photograph. Our acquaintance,

or the photograph, stand for the system **A** which informs us of system **C**. In the first case we are concerned with a living informing system, in the second case with an inanimate informing system. Let us remember that we obtain the majority of information not by direct contact with the system about which we want to learn something, but that there is frequently not only one, but a series of intermediary systems interposed between us, who want to be informed (i.e. system **B**), and the system **C**. The last of the systems thus interposed is then the one that conveys

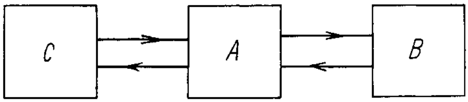

Fig. 13.2. The most complicated case of conveying information. System **A**, *the mediating system, is in two-way communication both with system* **B** *and system* **C**

information directly to us. Let us also remind the reader of the example of our learning from textbooks. The knowledge contained in them has usually been accumulated by many different "observers" who have communicated their observations to others, published them in papers and books, before everything was finally gathered in the textbook we mentioned. Or let us mention some travel film shot by some traveller and now shown to us in his absence.

13.2 The Proper Model

In order to understand the following sections, we must very clearly realize what system **A** can do with the signals received from **C**, which it will later use as a basis for passing information concerning **C** to system **B**. So as to be able to convey information, system **A** must first of all be capable of storing the signals received. It must therefore be equipped with a memory — no matter whether temporary of permanent. System **A** must also be capable of releasing, at the suitable time, the signals stored in its memory. If the system would store the signals in their original form and pass them on without changing their contents,

we would consider it as the simplest informing system. E.g., a tape recorder reproduces the signals received and does so moreover in unchanged order. A film that has not been edited but is shown as it has been shot can also be considered as a simple informing system. In these cases the informing system neither adds anything to nor subtracts anything from the information obtained from system **C**. A human being who simply reproduces what he has heard or read behaves in a similar manner.

If **A** is a more complicated system, it may be equipped with facilities for *processing the signals received.* In general, we are forced to admit such processing at all levels of perfection. What does the processing of signals received by system **A** depend on? So as to be capable of processing the received signals, system **A** must incorporate something called, at times, an instruction, at other times a method, rules, a routine, program, etc. When speaking of living systems we also say that they process the signals received on the basis of experience, with great keenness, with foresight, with invention, etc., and we thus simultaneously characterize the level at which the signals are transformed, changed, corrected, etc. We shall find that our vocabulary provides a wide choice of words for the description of this situation, expressing the subtlest distinctions between the kind and manner of the processing to which the received signals are subjected, and frequently also comprising the personal qualities of the system involved.

To unify our terminology, we shall designate all this by a common term and simply say, that system **A** incorporates certain *rules R*, according to which it processes the received signals. The term "rules" will thus be used to denote whatever instructions, directions, etc., may be employed to determine the manner in which the signals are processed in system **A**. In man, these rules are represented by procedures acquired by learning or by experience, sometimes tinged by emotional attitudes, momentary mental disposition, etc. In digital computers they are represented, for instance, by a program devised in advance, sometimes by a program prepared by the computer itself on the basis of its own experience (see Chapter 12).

System **A** thus receives signals from **C** and processes them in accordance with rules already contained in it or supplemented by itself on the

basis of the signals that are being received. It then inserts in its memory, on the one hand, the signals received, and on the other hand the signals resulting from processing. For the time being we are not interested in the time when the received signals are processed, i.e. whether this happens immediately on their receipt or just before system **A** passes on the corresponding information, or at any time between. We must only realize that the information on system **C**, passed on by system **A**, is based on the signals stored in the memory of system **A** and consisting of the signals received from **C** combined with the signals processed according to the rules *R*. Both these kinds of signal, stored in the memory, form a system which models the system **C** in system **A**. This system is called the *proper model of system* **C** *in system* **A** [B79].

13.3 Signals Constructing the Proper Model

Before proceeding with a definiton of the proper model, let us take a closer look at the kind of signals used by system **A** to construct a proper model of system **C** in itself. As will be seen, system **A** has a somewhat more intricate significance in this new interaction than before.

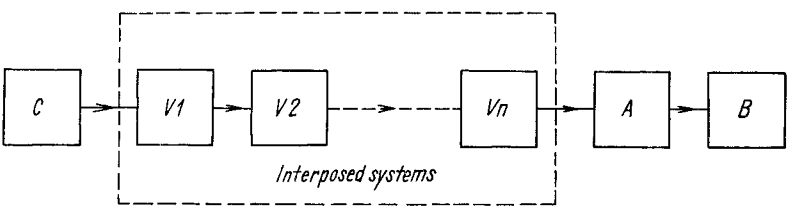

Fig. 13.3. Block diagram illustrating the case where the informing system **A** *is not in direct touch with system* **C**, *information on which it passes to system* **B**

We have already mentioned that system **A** need not always be in direct touch with system **C**, but that a number of further systems may be interposed between them, so that in this case system **A** acts on the basis of signals repeatedly processed by the intermediary systems. The situation is graphically illustrated in Fig. 13.3, where the interposed

systems are denoted by $\mathbf{V}_1$ to $\mathbf{V}_n$. System **A** cannot directly check whether the signals purporting to come from **C** are really such signals. We have mentioned that the rules, whereby systems process the signals received, include – where living systems are concerned – also rules acquired by experience, emotional attitudes, etc. It may thus happen that signals, received by system **A** as signals coming from **C**, actually need not be the signals they purport to be. This can be observed to happen very frequently in interpersonal contacts when the original information, transmitted from one human being to the other, is distorted – often unintentionally – to such an extent, that the last person in the chain receives information widely differing from the original. Moreover, it must be realized that system **A** mostly receives signals not only from a single system **C**, but that it obtains simultaneously a great number of signals from other systems which carry information on entirely different matters. Among the rules R (i.e. those which govern the processing of signals received from **C**), system **A** must therefore include rules according to which it will be able to select from the incoming signals those concerning system **C** alone.

These rules will be called *selective rules* and denoted by SR. Thus, it will now depend on rules SR whether a particular signal arriving in system **A** will be received as a signal pertaining to system **C** or not. And, since the selective rules (no matter how acquired) are a property of system **A**, we shall now take the view that, from the moment at which system **A** applies these rules, it is only its own concern whether it "considers" a particular received signal as a signal informing of **C** or not. We shall say that it regards this signal as a signal concerning **C** in case that it has added it to (or is going to use it henceforth as a part of) its proper model of **C**, no matter whether in its (i.e. the signal's) original or processed form. When system **A** utilizes a signal indifferently with respect to the proper model of **C**, we say that it does not consider this signal as coming from **C**.

If we use the words "system **A** considers every signal as a signal coming from **C**" etc. in this context, we do not want to imply that we want to ascribe a consciousness to system **A** in case this is inanimate. In an inanimate system, these words must be regarded from the viewpoint of an observer who describes the behaviour of the system without deciding

whether this behaviour is based on consciousness or not. We certainly realize that the essence of similar difficulties consists in that we want to give a general description of properties and situations common to living and inanimate systems which, however, we are used to designate by different terms according to the type of system concerned. Speaking simultaneously of both living and inanimate systems, we cannot avoid using a single type of expression.

Nevertheless, we shall introduce some further terms of this kind. We want to show step by step that, from the viewpoint of the observer, **A** is a system that takes its own attitude concerning whatever it receives from its environment, no matter whether it is a living or an inanimate system. Moreover, it is clear that the words "its own attitude" are meant to imply that system **A** selects and evaluates the received signals according to its rules R and SR. And by saying "its" we mean that these are rules which system **A** comprises and uses, without regard to whether it has created them on its own or whether they have been introduced in it from outside, as mentioned before. We are thus concerned with a type of decision-making and handling of received signals, that depends only on system **A** from the moment onwards when this system started to apply the rules SR (no matter how acquired). This is what we wanted to emphasize and what forms the basis for the behaviour of system **A** appearing to an observer as the subjective evaluation of signals received and as their subjective handling.

13.4 DEFINITION OF THE PROPER MODEL

Summing up the results of our considerations and using the following notation, we arrive at the definition of the proper model given below:

System **A** is a system that receives signals from system **C** or signals concerning system **C** (system **A** may also be admitted to observe system **C**).

System **C** is a system on which system **A** is supposed to supply information. This is the system from which system **A** receives signals or, to be more accurate, of which system **A** assumes to be receiving signals concerning it.

Definition: *The proper model* **CA** *of system* **C** *in system* **A** *is a set of signals received, processed and stored in its memory by system* **A** *as signals concerning system* **C**.

This definition respects all the conclusions arrived at on the basis of the foregoing considerations. It defines the proper model as a system located inside system **A** in the sense that it forms, for instance, its substructure. In a wider sense of the word, however, this also includes the case where system **A** has the chance of using a proper model that is not explicitly a part of itself. This can be exemplified by a person – as system **A** – who sketches on a piece of paper the things seen at a given instant. This person can later use the drawing thus produced to recall what he has seen at the given instant and how he has seen it. A similar situation is encountered when a person writes a book which he later draws upon. The sketch drawn or the text written, which in both these instances form the proper model of **C**, is not a direct part (or substructure) of system **A**, but can be included under the definition of the proper model of **C**. The paper itself acts as an auxiliary memory in which system **A** has stored the proper model.

The definition presented above states simultaneously that, from the viewpoint of system **A**, the proper model is a subjectively formed model simulating system **C** in system **A**.

The proper model **CA** stored in the memory of system **A** forms, for system **A**, the basis for supplying any information concerning system **C**. Let us assume that system **A** does not receive any further signals from **C**, but that the signals which form the proper model **CA** are being processed in system **A**. This may happen in a living system in the case that the system **A** is, for instance, a person who meditates on system **C** by recalling in his imagination individual parts of system **C** and supplementing them with his own knowledge acquired formerly, etc. In the case of an inanimate system the same thing may happen, for instance, in a digital computer which adapts the contents of its store as a result of a stimulus received from outside. By such a process the system **A** may, under certain circumstances, improve the proper model **CA** of system **C** so that, after some time, it will be able to supply far more information on system **C** than before.

Opinions are divided as to how, in living systems, ideas originate from the records stored in the memory and by what mechanism they are transformed. Conversely, in digital computers we can follow in detail in what manner changes take place in the contents of their stores. Information retained in the store must be taken out and transferred to the arithmetic unit. There it is transformed according to instructions contained in the corresponding program. After having passed through the arithmetic unit, the results are again inserted in the store. Thus, the arithmetic unit is the place where the contents of the store are transformed unless, of course, we simply want to clear the store and record something else. When a human being processes the information stored in his memory, we usually say that he recalls ideas, combines them, or transforms them in some other manner.

13.5 THE PROPER MODEL IN LIVING AND INANIMATE SYSTEMS

Let us now compare the individual stages in the formation of the proper model in living and inanimate systems respectively. In this respect we are not so much concerned with a mechanical transfer of concepts, as with an attempt to show the terminological deficiences preventing us from speaking in general terms of certain processes common to living and inanimate systems – that is, to speak of such processes without having to state which kind of system we are thinking of. We also want to get a better insight into the similarities and differencies between these processes in living and inanimate systems respectively.

If we consider the definition of the proper model, we are sure to realize that we are substantially concerned with the contents of memory. Not, however, with the contents of the entire memory, but only with that of a distinct part of it, namely that which holds the signals used by the system in connection with system **C**. Let us first answer the question of how the signals get into the memory and who supplies the necessary stimuli.

In living systems, these stimuli are supplied by their environment on the one hand, and by the system itself on the other hand. This is a combination in which the environment predominates at certain stages, periods

or even instants, the system itself predominating at other times. The share supplied by the environment is larger when the attention of the system is focussed on this environment. The share of the environment is smallest and that of the system itself the largest when the system is fully concentrated upon itself so that, at the given instant, it does not even perceive the signals of its environment.

In man, the storage of signals in the memory depends on his consciousness, a fundamental facility which plays the greatest part in this process [C28]. However, not every signal accepted by some receptor is permanently stored in the memory. From a certain stage of evolution onwards, living systems possess the faculty of consciously retaining information in their memory. In addition, information is inserted in the memory subconsciously. In our definition of the proper model we have spoken of the contents of memory without regard to whether they were stored consciously or subconsciously. Moreover, we did not always distinguish the kind of memory concerned. In certain cases, our definition need not always concern the memory supposed to be seated in the cerebral cortex of man. In this context the term memory is used in the technical sense, i.e. we regard as memory every element capable of retaining a given signal, coupling, or record. From this point of view we also regard the acquisition of a conditioned reflex as a record revealing itself in a combination of the pertinent signals, without our localizing this record. Similarly, when establishing stereotypes of behaviour, we regard the resulting activity as the contents of memory without wanting to imply that in this case it is seated exclusively in the brain. The main point of our definition is that there is simply some place in the system where the pertinent information is recorded, and that this place is designated as the memory without any claim as to its localization.

The selection of signals retained in the memory (in different stores of the system, or in elements capable of storing information) is performed in the living system sometimes consciously, sometimes subconsciously, i.e. without passing through consciousness. Let us remind the reader, for instance, of the allergic reactions of living systems, which need not have anything in common with consciousness; the system still exhibits the corresponding reactions because it has "learnt" to do so under certain circumstances and now it "uses" them under the same circum-

stances. From the viewpoint of the construction of proper models we shall thus consider the reception of signals not only from the aspect of consciousness. The recording of signals in the memory will simply be regarded as either performed or not performed, whatever part of the system is acting as the memory.

Living systems possess the faculty of receiving, classifying and recording certain signals. In inanimate systems this process can be observed to take place to a limited degree only. Thus, for instance, it can be seen in digital computers or other special machines utilizing experiential methods. In these cases a great many input signals are received, of which only some are retained in the memory, moreover in a processed and not in the original form. The remaining signals, which find no application in the machine from the viewpoint of the experience acquired, are either automatically forgotten or later eliminated.

A selection of input signals can also be observed to take place in so-called self-organizing systems that build up their structure on the basis of signals which are of some importance to their construction whereas other signals, unessential for this purpose, are automatically rejected. This process may also be regarded as an automatic selection among input signals, performed by the system. No such selection takes place, however, in classical inanimate systems. Nevertheless we may speak of a proper model in the sense of our definition. Before a digital computer starts solving any problem, we must first insert the prepared program in its memory. If the computer follows, for instance, the behaviour of an aircraft, its memory must contain, in the form of a subroutine, equations modelling this behaviour. These equations, incorporated in the subroutine, are contained in the memory of the computer and form according to our definition the proper model **CA** of the behaviour of the aircraft which here represents the system **C**. Here again it is quite clear that system **A** – the digital computer – can answer questions concerning system **C** only on the basis of the proper model **CA**, i.e. on the basis of the inserted equations and of the pertinent method. It is also clear that its answers will do justice to our questions only in so far as the proper model **CA** does justice to system **C** to which our questions refer.

In this case, the proper model has not been established by system **A** alone. It has been constructed by a human being who also inserted it in

the system. Our definition, of course, does not presume that the proper model must be an independent creation of system **A**. On this occasion we should also realize that many of the proper models possessed by some person have not been created by himself but that, quite on the contrary, a great number have been taken over from books, from hearsay, from school learning, etc., i.e. they were created by other people. These proper models have thus been taken over ready-made from elsewhere.

An interesting attempt to model the complicated behaviour of an organism is exemplified by A. SVOBODA'S *model of the self-preservative instinct* [B72]. This model is the first inanimate system described in literature that is capable of creating, on its own, the proper model of the room in which it moves about. We are thus concerned with an inanimate system that forms its own foundations for its behaviour on the basis of signals received from the environment.

13.6 TRANSFER OF THE PROPER MODEL FROM SYSTEM A INTO SYSTEM B

In the preceding sections we regarded the proper model as a system, established by system **A** in itself as a substitute for system **C**. The proper model has been constructed on the basis of signals interpreted by system **A** as signals concerning system **C**. The system set up in this manner and designated as the proper model **CA** of the system **C** in system **A** is utilized by the latter whenever it receives a question regarded by it as a question concerning system **C**. From a slightly different point of view, the proper model **CA** in system **A** can be said to be a model of system **C**, created within itself by system **A**. When asked questions concerning system **C**, system **A** does not answer according to the real system **C**, but on the basis of a knowledge of its model.

We shall now direct our attention to the situation when system **A** conveys its information concerning system **C** to some other system, called **B** (see Figs. 13.1 and 13.2), assuming that it is no longer in touch with system **C** at the time it passes the relevant information. System **A** has then only the proper model **CA** at its disposal. The ideal situation, when system **B** might be fully informed of system **C** by system **A**, is

then quite out of the question. This is because system **A** no longer communicates with system **C** itself, but only with its model. System **A** is therefore capable of informing system **B** on system **C** only in so far as it can use the proper model **CA** for this purpose.

For the following reasons, the situation thus arising is very complicated.

1. System **A** contains a model constructed on the basis considered by it as signals concerning **C**. The proper model **CA** need therefore not always correspond to system **C**. In certain instances, of course, the proper model **CA** may be correct. In that case everything is in order. At other times, however, the proper model **CA** may be only approximately correct, or even quite incorrect, i.e. if it is based on an erroneous interpretation of the signals. The information later transferred to system **B** will then, of course, be also incorrect. This is a situation characterized by the well-established saying, that system **B** has been misinformed.

2. System **A** has combined the received signals to form a proper model according to certain rules. Now, if system **B** obtains signals concerning system **C**, these signals having been derived by system **A** from the proper model **CA**, system **B** will also produce a proper model of system **C**, called the proper model **CB** of system **C** in system **B**. If system **B** receives the same signals (which, in some cases, would have to follow one upon the other in the same order) as formerly received by system **A**, and if it uses the same rules to construct the proper model, the same proper model of **C** can be established in system **B** as in system **A**. Actually, however, the situation is different. System **A**, which already has the proper model ready, need not present its information concerning system **C** to system **B** by means of the same signals and in the same order as received by itself. Moreover, if it has made its own additions to the proper model **CA**, it can transfer them directly to system **B**. It is true that, when systems **A** and **B** interact, the proper model is gradually transferred from system **A** to system **B** but, in general, by signals differing from those which caused it to be established in system **A**. The fact that in this case system **B** uses the same rules to construct **CB**, does not guarantee that the proper model set up in **B** will be the same as in **A**.

3. Finally, it must be said that even if the same proper models of system **C** are established both in system **A** and **B**, this still does not mean

that both systems will utilize their proper models in the same manner. It is important to realize this because, in complicated cases such as the generation and use of proper models in higher types of living systems, we can ascertain what a given proper model looks like only on the basis of questions put to the system. The answers of the questioned system will enable us to get a picture of its proper model only according to the manner in which it is used by the system. If, in this process, reactions take place that are considered as incorrect, this need not always be caused by the corresponding proper model being incorrect. The reason may just as well lie in the system using its correct proper model in a wrong manner.

Let us note in the following sections, in what manner this difficult situation is solved in the interactions of the most highly developed systems – in human beings – that use speech as the most common method for transferring their proper models. Let us also notice what problems and possibilities follow from this aspect for the use of language between inanimate systems.

13.7 Language as an Instrument for the Transfer of Proper Models

From the point of view, expanded in this chapter, every interaction effected by speech, gestures, conventional symbols, etc., may be regarded as an interaction whose goal it is to transfer proper models from one system to another one. Let us see what safeguards must be taken when using language, so as to make sure that this interaction accomplishes its task (see also Chapter 15).

Let us start with the following situation. Person **A** was in room **C**, where he saw the following: in the centre of the room there stands a table, on the table lies a book, next to the table stands a chair. Some time later, person **A** wants to convey to person **B** what he has seen. For this purpose he uses language and pronounces the sentences we have employed above to describe the situation observed.

Since person **A** is no longer in contact with room **C**, he must use for the description of the situation observed a proper model of system **C**,

according to which he forms a mental image of what he has seen. He transforms this mental image into a verbal expression, which has two aspects:

1. The words used have their meaning. This meaning serves to evoke in system **B** the same mental image as in system **A**. Thus, the words table, chair, book, etc., must evoke the mental image of a table, chair, book, etc. A necessary condition is that system **A** use the same language for this interaction as system **B**. In this context, language appears as a code which assigns a distinct meaning to a given sound, a group of vowels and consonants, etc. For instance, the meaning ascribed to the group of sounds *b*, *o*, *o*, *k*, written or pronounced together, is the object known as "*book*". This conventional assignment, acquired by man, causes these sounds to evoke in a visual type a very lively image of the book seen before. This is a process called association; translated into the language of machines, it would read like this: According to an address made up of the sounds of "book" find a photograph marked with these sounds. The photograph illustrates the object denoted by this particular group of sounds.

When we say that both systems use the same language, we mean thereby that they assign the same objects etc. to the same groups of sounds, words, etc. In other words, they use words in the same sense.

2. The sentences pronounced have their grammar, i.e. words used in the sentence are arranged in a particular manner, with certain endings, prepositions, conjunctions, etc. The grammatical aspect of a sentence says in which manner the words are interrelated. From the viewpoint of the forming of ideas, grammar represents an instruction of how to link up partial images into a total resulting idea. Using the terminology of machines again, grammar is a program prescribing the operations to be performed on partial images so that they are grouped together to form the resulting correct idea. This is not to say that, for instance, when reading a long paper we can keep the entire idea of its contents all at once in our imagination. For the sake of clarity, it will therefore be better to expound in a more accurate manner all that has been said before.

Grammar is a program in accordance with which the meaning-contents of words are processed so that a proper model is set up in

the memory, this model being used for recalling the resulting ideas corresponding to the contents of whole sentences as well as to the contents of the entire text.

In order to ensure that the instruction transferred from one system to the other by means of language be effective, both systems must use the same language and the same grammar; alternatively, an intermediary system (an interpreter) must be employed, capable of correctly transforming the languages and their grammars.

In this connection we should like to remind the reader that not only words, but also gestures, facial expressions, conventional signs, optical, acoustic and other signals may have a conventional meaning whereby communication can be accomplished, i.e. by means of which it is possible to transfer proper models in the sense of our conception. As far as conventional signs and gestures are concerned, the exchange of information is mostly based on conventions used in language. According to some authors, such communication is always based on language. However, the information derived from the accent given to words and from its modulation, from facial expressions, etc., may form quite independent signals which are in no way based on the prior knowledge or use of any language.

CHAPTER 14

PERCEPTION AND ITS DISORDERS

14.1 THE PERCEPT

According to the type of sensor through which a signal enters the organism, we speak of visual, auditory, tactile, olfactory and other percepts. We say that the corresponding percept concerns the pertinent sense – sight, hearing, touch, smell, etc. The signals passed on to the organism by the stimulated sensors are called *sensations*. The sensation is transmitted to the central nervous system, where it is modified and supplemented on the basis of prior experience. The momentary state of the system (its "state of mind"), its degree of attention, the contents of its memory (the stored prior percepts) and some other factors also contribute to this process. The percept is thus the result of a complicated action of the nervous system, initiated by a sensation.

In digital computers with provision for time-sharing, the information does not arrive in the memory proper in the form picked up by the corresponding sensor. For instance, in a card reader the signals are sensed in quite a peculiar "mixed-up" order, in a manner most satisfactory from the technical point of view. Inside the card reader the individual signals are then rearranged so as to be suitably adapted to further processing. The signals are fed into the computer proper only after having been "reprocessed" in this manner.

In inanimate systems we encounter various input devices which, to a certain degree, may quite rightly be compared to the sensors of a living organism. However, as far as the counterparts to the "*senses*" of living organisms are concerned, neither the corresponding designations nor, for the time being, the need to introduce them, will be found to exist in connection with the inanimate world. This is probably because in inanimate systems we dispose of such a great number of different methods for receiving information from their environment. We therefore prefer to speak of the corresponding sensor rather than of its classi-

fication from the point of view of its faculty to react to a distinct type of signals. Nevertheless, attempts are known to have recently been made to equip machines, for instance, with optical paths for the reception of information, which we designate as the visual perception of the machine. The mechanical reading of punched cards is often referred to as sensing, etc.

The term "sensor" thus appears to be suitable for the common designation of the place (sub-system, unit, whole) at which signals from the environment enter the system. Similarly, the term "sense" seems to be suitable for the designation of the capacity of a system for perceiving signals of a particular kind: the *visual sense* for the capacity of perceiving optical signals, the *tactile sense* for the capacity of perceiving signals obtained by contact of the pertinent part of the system with its environment, the *auditory sense* for the capacity of perceiving acoustic signals, the *olfactory sense* for perceiving the composition of gases, etc. At the present, the *kinesthetic sense* cannot be interpreted with respect to inanimate systems; similarly, the capacity of a radar set for perceiving centimetric waves has no analogy in man, who is not equipped with this capacity. To-day a broader use of the term "sense" as applied to inanimate systems does not appear to be sufficiently justified.

Let us remind the reader that there are considerable differences in the animal kingdom as to the sensory equipment of various animals. Some animals have no sight (earthworms, deep-sea animals, etc.), others have no hearing (lower animals). On the other hand the bat, for instance, is capable of perceiving signals of ultrasonic frequency – a feat of which man is incapable.

14.2 THE MENTAL IMAGE

Many living systems are capable not only of storing percepts in their memory, but also of recalling them as required in the form of mental images. The mental image can be reinserted in the memory and then recalled again. According to the facilities of the particular system, mental images can then be treated in various ways, transformed, combined, etc. Even the resultant mental images which have been com-

bined or transformed can again be remembered, i.e. stored in the memory.

The term "mental image" has not yet been used in connection with inanimate systems, even though the processes mentioned also take place in them. The signals received by the input devices are inserted in the memory of the machine whence they are extracted so that the machine can handle, transform, classify or combine them. After concluding their manipulation – performed, for instance, in digital computers by the arithmetic unit – the transformed signals are again stored in the memory. However, such signals need not always be subjected to a transformation. In classifying operations, for instance, we are concerned only with a re-arrangement in the memory. When a living system recalls a mental image, we say that it is becoming aware of it. In inanimate systems we do not yet speak of awareness, since it is not quite clear what such a designation can be assigned to in the sense of modelling. Thus, we shall disregard the process of "becoming aware", which is a subjective experience in the forming of mental images, and shall confine ourselves to the statement that the recalling of a memory record for the purpose of forming an image serves the internal needs of the system. The recalled image is a basis for decision-making, contemplation, combination, construction of hypotheses, and for many other purposes. The manipulation of a mental image can result in its reinsertion in the memory, or in its providing a stimulus to some action, no matter whether its effect concerns an external manifestation of the system, or a manifestation serving its internal requirements.

Let us consider in detail how a digital computer deals with the signals recalled from its memory.

The read-out signal is supplied by the control unit, which conveys the recalled signals from the memory to the arithmetic unit. According to the instructions of the control unit, the arithmetic unit processes, transforms and modifies the signals and reinserts them in the memory. Since we are concerned with machines designed, in the majority of cases, to treat problems formulated mathematically, the arithmetic unit performs mostly arithmetic operations, i.e. the transformation of signals based on mathematical relationships. However, these operations are not the only ones possible. Whenever necessary, the arithmetic unit also pro-

cesses instructions, which it transforms, supplements, etc. We are here faced with a situation where, properly speaking, the arithmetic unit alters the program according to which the control unit operates. The arithmetic unit thus not only processes and transforms the signals appertaining directly to the numerical contents of the program and of the memory, but also adapts and changes the working procedures according to which the control unit is to operate. The arithmetic unit thus enables the control unit not only to perform passively the required computation, but also to influence its own operation.

However, the control unit does not follow the adaptation of its own program, so to say, actively. The resulting signals obtained from the arithmetic unit are passively reinserted in the memory, whence it extracts them passively again at the suitable moment. Nevertheless, there is one element of behaviour which can be called active. This is the signal supplied to the control unit directly from the arithmetic unit, the signal which immediately affects the operation of the control unit. In classical digital computers this is the signal guarding the sign of the result of the operation which is being performed by the arithmetic unit. This signal immediately affects the further procedure to be selected by the control unit. The control unit thus follows the operation of the arithmetic unit and adapts its own operation to the results of the arithmetic unit only by means of this single signal which has an immediate effect on its further operation. In digital computers featuring time-sharing facilities there are several types of such signals which affect the control unit directly according to the result of operations performed by the arithmetic unit.

Compared with the manifestations of a living system, the arithmetic unit can be most suitably regarded as the seat of imagination, where the term imagination is considered to mean the transformation or recombination of images. In a computer we are then concerned with a transformation controlled by the control unit on the basis of the program and of the instruction code, i.e. with some kind of controlled imagination (constructive imagination).

If we wanted to describe this state of things in terms common to the living and inanimate world as introduced before, we might say that in the arithmetic unit the computer imagines numbers, recalled from its

memory on the basis of rules built into the arithmetic unit and on the basis of stimuli supplied by the control unit in the form of the instruction code. The computer processes the recalled (or imagined) numbers in its imagination and stores the results in its memory. In its arithmetic unit the computer is also capable of imagining instructions, which it also modifies and then stores in its memory as required.

To continue with this metaphorical language we say that "*the control unit does not take note*" of these images, i.e., it does not act according to them or according to their final products, with the exception of the decision signals mentioned above.

The description of the operation of a computer expressed in this way sounds very unusual. However, we must accept it from the viewpoint of the possibility of descriptions common to living and inanimate systems. This acceptance must, of course, be based on an agreement as to which processes of the living world on the one hand and of the inanimate world on the other hand will be designated by a common name. Of course, this does not mean that we declare both processes to be equal without regard to the viewpoint from which we assess them.

From the point of view of what we said about percepts, mental images and imagination, and of what has been expounded in Chapter 12, the proper model (**CA** of system **C**) is represented in living systems by those percepts and images stored in the memory, which the particular system considers to be related to system **C**. In other words, *the proper model* **CA** *of system* **C** *in the living system* **A** *is formed of the contents of that part of the memory, which holds the percepts and images of system* **A** *concerning system* **C**. When system **A** operates with the proper model **CA**, it recalls it part by part from its memory and transforms it in its imagination. Complicated living systems are capable of retaining in their memory many proper models of various systems at the same time.

In inanimate systems, e.g. in digital computers, *the proper model of* some *system* **C** *is represented by signals stored in the memory as signals concerning system* **C**. The proper model is formed by the contents of that part of the memory which holds the signals selected by the computer when working on this proper model. When a digital computer operates with its proper model, it recalls it part by part (i.e. word by word, sometimes block after block) from its memory and transforms it in its arith-

metic unit. More complex digital computers provided, for instance, with time-sharing facilities, are capable of concurrently operating with several independent, mutually unrelated, proper models.

14.3 THE PROCESS OF PERCEPTION

The process of perception is described as a process in which the entire personality participates. This concerns not only the reception of signals from the environment. Perception is related to many other circumstances, such as the supplementation of percepts and experiences, the participation of images in the supplementation of percepts, pleasurable or apprehensive expectation, emotional effects, the interpretation of percepts, the momentary disposition of the organism, its degree of attention, etc.

If we try to establish a common viewpoint concerning perception in both living and inanimate systems, we must realize that, under present circumstances, we neither can nor want to apply this point of view into all details. First of all, this is because the individual terms used to describe living systems are not yet defined so as to be simultaneously applicable to inanimate systems also. Anyway, this is just what we are going to attempt to do with some of these terms. Secondly, some of them have no meaning when applied to inanimate systems. It is not our intention to show that all kinds of percepts occuring in connection with man can also be found, for instance, in the behaviour of digital computers. We only want to show to what degree the perception of man may be compared with that of digital computers, and from what point of view these types of behaviour can be regarded as being similar.

Thus, for instance, we cannot speak as yet of attention in inanimate systems. Still less can we speak of an emotional component in their behaviour. Even though psychiatry emphasizes the great importance of emotions to disorders of perception, we cannot yet deal with the problem of emotional effects upon disorders of perception in inanimate systems. At the present we do not know what manifestations of inanimate systems may be considered as emotional, although there is no lack of reason why inanimate systems should not be equipped with emotional

capabilities. We clearly feel that without similar facilities it would be difficult to speak of the artistic abilities of a system, of its impressions and emotional experiences, which would enable an inanimate system to evaluate, similar to man, a work of art from the point of view of impressions, agitation, tension, satisfaction, etc.

We shall conduct our further investigations so as to leave room in our deductions for a later supplementation of aspects which are as yet inaccessible. For instance, the manner in which a system deals with the received and recalled signals is broadly called *rules* (see Sec. 13.2 et seq.). When using this term we do not mind if the rules are understood to comprise, for instance, effects acting on the transformation and processing of signals. As we are taught by psychologists, these effects or – in our terminology for inanimate systems – rules can be represented by emotions or other manifestations depending, say, on the momentary internal state of the system.

Our definitions will then be concerned in particular with the common traits of a distinct group of manifestations. Our considerations will be applicable to situations where the points of view from which we started will not undergo any subsequent changes.

We might raise the objection of why we are looking for common traits that do not do full justice either to the living or the inanimate world and why, based on the limited validity of such considerations we want to introduce, for the inanimate world, concepts that do not fully express the essence of the matter. In this case we must refer the reader to what has been said before and what we are systematically returning to:

1. We cannot transfer concepts, used in one field, to any other related fields without a restricting viewpoint. As will be seen, such transfers are made in many branches of science, and these branches benefit from them.

2. Even though our point of view constitutes a limitation on the one hand (from the viewpoint of individual systems), it is more general on the other (from the viewpoint of a generalized system). This point of view offers the possibility of using a broader aspect of the matter, and thus facilitates the description of common laws of behaviour.

These two reasons alone provide sufficient justification to search for such comparisons and to use them as a basis for further considerations within the framework of the pertinent point of view.

14.4 Disorders of Perception and Disorders of its Subjective Interpretation

In psychiatry we encounter many descriptions of disorders in living systems which can be called, according to our terminology, disorders of perception, disorders in the interpretation of this perception, as well as disorders of what we have called the proper models of systems. The concept of the proper model, explained in Chapter 13, permits us to present in a quite natural manner the following statements:

1. The proper model is associated with higher types of system behaviour.
2. Incorrect treatment of the proper model leads to disorders of behaviour in the sense that incorrect behaviour sets in, characteristic of different types of disorders.
3. The types of disorders arising from such incorrect treatment of the proper model strikingly resemble so-called mental disorders in man, as described in some cases by psychiatry.

14.5 Introduction of a Common Terminology

When a system bases its behaviour on the use of proper models (see Chapter 13), some peculiar disorders may ensue. It will be interesting to compare them with disorders which can be observed in cases called disorders of perception, disorders of consciousness, etc. In order to be able to speak of a system, no matter whether thinking of a living or inanimate system, we must establish a common terminology which will help us to show that we are concerned with similar, comparable phenomena, and which will simultaneously help us to correctly translate the terms used into the living or inanimate world, as required. The following descriptions (or working definitions), by means of which the common concepts are introduced, play in the sense of modelling the part of equations of mapping which enable us to correctly understand the common properties. We do not claim the descriptions to be complete, as is the custom when introducing definitions. Here we only want to characterize in outline the corresponding concepts so as to enable the reader, who is not accustomed to these terms, to

check his ideas accordingly in the course of reading the further text. In connection with every term we present, in the first place, a description expressing it from the viewpoint of psychology or, where applicable, psychiatry, in the second place a description from the viewpoint of engineering:

Stimulus – effect of signal upon a sensor,
– effect of signal upon an input.

Sensation – reaction of sensor to a stimulus,
– reaction of input to an input signal.

Percept – a sensation supplemented by the prior experience of the system,
– an input signal transformed by the input program.

Mental image – recalled contents of particular place in the memory,
– recalled contents of particular place in the store.

Seat of imagination – the cerebral cortex,
– the arithmetic unit.

Imagination – imagination (controlled and uncontrolled),
– operation of arithmetic unit (controlled by the program and the control unit, work performed in the arithmetic unit and intended for the internal needs of the computer).

Final image – image obtained as the final product of imagination,
– result obtained by the operation of the arithmetic unit.

Consciousness – a state of the system accompanied by the normal generation of concepts, the forming of images in the imagination, their recalling, combination and reinsertion in the memory, their control, and the establishment of correct relations between mental images and reactions,
– a state of the system accompanied by the arithmetic unit operating in correct contact with the store and the sensors under the control of the control unit, the results affecting the work of the computer being correctly interpreted by the latter.

Program – a source of control signals for a controlled imagination, and of centrally governed manifestations,
– a source of control signals for working the control unit.

14.6 Disorders in the Construction and Use of the Proper Model Compared With Disorders of Perception

It may happen that some disorder occurs while the proper model is being constructed in the system. According to the type of disorder, the system starts behaving in a characteristic manner. Let us go through some of these disorders:

1. A signal arriving at a sensor is correctly transformed by the input program and is passed to the system proper. Owing to some defect, however, the system interprets it as a different signal. For instance, a digital computer controlling a complex system correctly detects temperatures by means of a sensor, but owing to some internal defect it handles this information as though it were pressure. Such defects may have different causes. Some of them may be the incorrect connection of a sensing device, or cross-talk in the input lines, but it may also be an error in the program which controls the processing of the picked-up information.

If a similar type of disorder occurs temporarily in man, and the affected person is capable of ascertaining within a short time that he has incorrectly interpreted an input signal, we speak of a *mistake*. If the affected person persists in its incorrect interpretation owing to so-called psychological disorders, we speak of *illusions*. The symptom common to living and inanimate systems is that the system interprets a particular percept in an erronous manner.

2. In the course of constructing a proper model, due to some disorder signals may be generated which are incorrectly interpreted by the system as though they were signals coming from the input. For instance, let a digital computer read some record from its store. The program which processes the corresponding problem handles these signals as though

they were coming from a sensor. For example, when controlling a certain process it exchanges the information extracted from some part of the store for signals concerning the temperature picked up by a heat detector. Again, the causes of such disorders may widely differ. We may be concerned with an incorrectly devised program. Or the program may be correct, but some of the critical instructions may have been inserted in faulty parts of the store. A correctly prepared instruction, recorded in the store, may be read at the required moment as a different instruction. In a concrete case, the instruction to pick up a temperature by a heat detector may by read as an instruction to read some particular part of the store. The arithmetic unit thus receives the contents of the store, whereas the control unit, which performs the program, "supposes" that it is concerned with values detected by the heat detector.

This type of disorder resembles *hallucinations* – a condition when the patient reacts to his own mental images as though they were real percepts. Cases are not uncommon when the affected person is heard to speak in a loud voice to some other person who is not present, or is afraid of a lion which he believes to stand in the corner, etc.

The meaning of the concept of hallucination, common to the living and inanimate system, and thus also to a general system, is that the system accepts its images (or some of them) as real percepts.

3. A peculiar disorder occurs when the system uses incorrect rules in establishing its proper model. The result is an incorrectly constructed proper model. The reactions, derived by the system on the basis of this model, evoke incorrect system behaviour. A complicated situation arises particularly when the rules governing the construction of the proper model are set up by the system itself, for instance on the basis of its own experience, or in some similar manner. In such cases the system also verifies the validity of the rules. If the system does not have enough opportunity to test their correctness, it persists in using them. The behaviour of such a system will show to an observer that the fault lies in an incorrectly constructed proper model.

Again, the incorrect construction of a proper model, or the use of an incorrect proper model, may be due to very different causes. For our purposes the case is important when the use of an incorrect proper

model is caused by some internal defect of the system, for instance when the system for some reason "refuses" to apply tests which would show that it is concerned with a wrongly set up proper model.

This case resembles the disorder called, in psychiatry, a *delusion*; the patient morbidly persists in his convictions, imaginations and erronously derived behaviour in the face of strong evidence to the contrary.

The symptom common to the living and the inanimate system is that the system correctly utilizes a wrongly set up proper model.

It would be interesting as well as instructive to perform a more profound analysis of possible disorders in the construction and use of proper models. Alas, we cannot devote any more space to this problem. May our remarks serve at least as stimuli to further contemplation.

14.7 How Do Disorders of Perception Arise?

We should realize that there is no sense in speaking of disorders of perception in general in connection with every system. In Sec. 14.5 we presented a comparative table, introducing a terminology common to living and inanimate systems, and thus simultaneously a general terminology applicable to the general system.

To be sure, there would be no sense in speaking of hallucinations in lower animals. Similarly, there is no sense in speaking of hallucinations in a motor car, etc. If some particular term is to have sense, the corresponding system must satisfy certain assumptions. It must be equipped with sensors and with a memory, it must have facilities for constructing proper models (or at least to take them over and store them) and facilities for using proper models to derive reactions to the input signals. In the introductory chapters of this book we already took the stand that we must first define what we mean by a system. From this point of view we can now enunciate the following precise statement:

To be able to speak of disorders of perception in a system, it must be possible to define sensation, percept, proper model and mental image on the system in such a manner that these concepts possess a distinct sense from the viewpoint of the observed as well as from the viewpoint of the observer.

14.8 Elimination of Disorders of Perception in Computers

From the viewpoint of the manner in which disorders of perception can be remedied in computers, the measures to be taken can be divided into two types:

1. *The disorder of perception is due to a defect in the system proper.* To remove the disorder, we must intervene in the system. For instance, the faulty part of the store must be replaced by a new one. At other times, faulty insultation results in cross-talk between the conductors. Sometimes it will be necessary to replace an entire electric circuit which has started working incorrectly as a result of ageing or owing to the overheating of some component.

This type of disorder is characterized by the fact that we must intervene from the outside if we want to eliminate the defect in the system. In inanimate systems such an intervention is called a *repair*, in living systems a *surgical operation.* In case of necessity, let us admit for the general system either of these two terms for designating the removal of a disorder of this type.

2. *The disorder of perception is caused by a defect in the proper model,* an error in the rules or a defect in the program. The disorder cannot be cured by repairing the system proper, which is free of faults as such. Essentially, the disorder concerns the contents of the memory of the system, which holds the proper models as well as the rules for dealing with them.

The contents of the memory can usually be affected through the inputs. For instance, in simple cases it is possible to replace a faulty program by a correct one. This can be easily done in a digital computer which operates according to a program prepared in advance. The situation is more difficult when the computer sets up the corresponding program by itself. The fault is then difficult to discover. However, the greatest difficulties are encountered when the program is affected by the experience accumulated by the system. The program cannot be exchanged, because the relevant subroutines are not accurately known. And it is extremely difficult to reconstruct a program simply by having the contents of the store printed out on paper. In such cases we are reduced

to correcting the program by "asking" the computer various "questions" which are then "answered" by it. Only by analysing the corresponding answers can we arrive at conjectures concerning the reasons for the incorrect behaviour of the computer.

It is characteristic for this type of disorders, that they may be cured by intervening in the program of the computer, in the method by which the computer prepares its program, etc. It is essential that, in the course of this process, the computer receives signals from outside through its inputs only. This method resembles *psychotherapy*, in which a patient is treated by personal consultation, by being brought to face certain situations, by being submitted to corrective experiences, etc.

In these cases, the feature common to living and inanimate systems is that corrections of behaviour are attained by means of input signals, without directly intervening in the system. Whenever necessary, let us admit the term "psychotherapeutic" for this type of intervention in a general system.

14.9 Can an Inanimate System Have Consciousness?

When discussing the problems of higher behaviour in inanimate systems we frequently encounter a question which, when answered in the affirmative, might arouse a thousand objections: Can an inanimate system have consciousness? We do not want to discuss this question here from the standpoint of subjective opinions. We would like to show that it can be treated quite seriously and that we can arrive at quite real results, if we put it in the right light. Since we are concerned with a very delicate problem, we must again make quite clear what we mean by modelling, what can and what cannot be ascribed to a model.

In the preceding sections we have already mentioned that in a model of behaviour we require that the stimuli and corresponding responses in the system to be modelled be isomorphic with the stimuli and responses in the modelling system, over the entire range determined by the point of view from which the modelling system is regarded as a model of the modelled system. We have thus admitted that, for instance, in the graph of a function the independent variable be represented by the length of

a straight line section, or that the flow of water in a dam be modelled by an electric current, etc. In modelling it is thus not essential that an entity given in the original be simulated by the same entity in the model. However, it is essential that, first of all, the behaviour of the modelling system belong – as far as its internal structure is concerned – to the same class (see Sec. 10.6), or within permissible limits to approximately the same class as the behaviour of the modelled system and, secondly, that the mutual mapping between input and output signals be known, so that the behaviour of the modelling system be transformable into that of the modelled system. As already stated, the mapping forms a viewpoint from which the modelling system is regarded so that the behaviour of the modelled system is seen in it. Figuratively speaking, it forms spectacles through which we view the modelling system so that we see the modelled system in it.

Not only the signals and the component elements of the modelling system differ from those of the modelled system (the systems not being identical), but the properties of the two systems are also different. However, if the purpose of the model is also to simulate certain properties of the original, these properties must also be "viewed through the spectacles of the selected viewpoint", i.e. we must know their mapping.

It must be said which property of the modelling system simulates that or the other property of the modelled system. In order to make the mapping of properties obvious even in complicated cases without protracted considerations, a method is frequently chosen which is applied to modelling by an unwritten agreement, but often misunderstood owing to ignorance of the matter, thus leading to distorted and inconsequent opinions with respect to modelling. To avoid the necessity for a lengthy description of the mapping, the same terms, i.e. a common terminology, is used for those elements of behaviour and for those properties which are to correspond to each other. A graphic example of this procedure is the method already used in Sec. 14.5, where we introduced for certain facts and properties a terminology common to living and inanimate systems. A common terminology also permits us to describe the behaviour of the modelling and the modelled system simultaneously. A description of the behaviour of different systems by common terms – provided these terms are properly introduced – permits us not only to

compare different systems, but at the same time directly determines their mutual mapping.

Before answering the question presented at the beginning of this section, let us dwell for a while on the mapping of properties.

14.10 Isomorphic Properties of a System

If we introduce a common terminology for the behaviour of different systems, as just described, this does not mean that the two systems have the same properties in the sense of being equal. Their properties are equal only in the sense of the mapping introduced by the common terminology. For instance, when saying that the electrical model of a dam shows how the water flows in it, we do not mean to say that water flows in our electrical model, but that the water is there in the sense of the mapping. The electric current in some distinct place of the model is regarded as the flow of water (represented by the current).

Thus, if we have two different systems described by the same terminology, we do not ascribe the same properties to them, but properties represented one by the other. To express our meaning clearly in the expositions to follow, we shall designate the property of the modelling system by the term "mapping property" or, when suitable, by the term "isomorphic property".

We must linger on yet another point. When saying of two people that both possess a heart, we do not mean to say that it is the same heart, i.e. that we are concerned with identical hearts. What we have in mind is, that each of these persons has an organ called "heart". These hearts resemble each other to such an extent that we designate them by a common name. However, they "resemble" each other to a certain extent only. For instance, they may differ in weight, each of them may work in a sligthly different manner, etc. The common name means that these hearts have some properties in common, but not that these organs are identical. Similarly, if we speak of some living organisms having a consciousness, we thereby say that they have something in common to which we assign this term, as far as some properties are concerned. We do not mean to say that they have an identical consciousness.

Since we are concerned with a name common to the consciousness of different people, we are also concerned in every case with a different consciousness. Thus, one consciousness may serve as the model of another one, in the same way as the heart of one person may act as the model of the heart of another person. It is true again that this heart may serve as a model from certain viewpoints only (not from all the possible ones). Thus, if we compare the consciousness of two people, similarly to the comparison of two different hearts, we must regard them as isomorphic or mutually representing only from a certain viewpoint, but not as identical.

We are now ready to revert to our original question of consciousness in inanimate systems. Since consciousness is a property of living systems, and we are interested in its existence in inanimate systems, we thereby clearly say that we are not concerned with a comparison of two identical systems. Therefore, to be more accurate we necessarily ask by this question, from our point of view, whether an inanimate system can be equipped with something which we might compare with consciousness in a living system. In the sense of our prior considerations we are now concerned with finding or creating in an inanimate system a representing consciousness or, if we are lucky, an isomorphic consciousness.

14.11 On Definitions of Consciousness

On examining publications dealing with consciousness, we have not found any satisfactory definition of consciousness. Nor is there any definition that would be generally acceptable. Still less do we consider ourselves competent to attempt such a definition. However, if we want to speak of the isomorphy of consciousness, it would seem that we have to start necessarily from some of the existing definitions. And here we are suddenly faced with an interesting and surprising fact: If the system satisfies certain assumptions, isomorphy of consciousness may be found in practically every definition of consciousness. We shall show in the following sections that this is really true. Before doing so, however, we should realize that it is of no importance what definition we start from provided it is properly chosen, this choice being dictated by purely

didactic reasons. Obviously, in the course of our exposition it will be far more important to realize what the relevant assumptions are.

The latest discoveries in psychiatry and psychology lead us to regard consciousness as a certain state of the organism. Thus, for instance, we speak of full consciousness, superficial or deep unconsciousness, clouded consciousness, sleep, etc. This conception of consciousness differs from older views, according to which consciousness was seated in a certain centre, nay even in an anatomically localized centre. In accordance with the latest conception we start in our considerations from the conception of consciousness as a state of the system. For our purposes we shall content ourselves with a rough description of this consciousness, without claiming either completeness or absolute accuracy. We shall leave an accurate description to those more qualified for such work and shall adhere to the matter as introduced in Sec. 14.5. Substantially, we are thus primarily concerned with a state in which the system is capable of performing its higher psychical functions, i.e. with the state of full consciousness. It will now depend on the particular definition, which of the relevant facts will be included in the definition of consciousness. As already mentioned, the accurate wording of this definition is not essential to us at this stage.

The activities performed by the system in the state of consciousness consist of the partial actions enumerated in Sec. 14.5 under the heading "Consciousness". In consciousness we are thus concerned, for instance, with a particular combination of partial activities, such as the generation of mental images on the basis of signals extracted from the memory, the generation of percepts on the basis of sensations, the concentration of attention, etc. The mechanism by which these activities are linked together may be envisaged in the most diverse manners. However, present psychology does not supply an unequivocal answer as to what this mechanism is like, i. e. how the individual partial activities are interconnected. As we are immediately going to show, however, even this ignorance presents no obstacle to our considerations. The abundant experience available in the sphere of modelling, performed not only in the field of automatic data processing, but also in many other branches, goes to show that so far every original has proved capable of being modelled, provided there existed a sufficiently clear description, simulta-

neously expressing the viewpoint from which this original seems interesting. This fact entitles us to say that, if the mechanism which links the individual activities in the consciousness can be found, it will also be possible to model this interconnection in an inanimate system from the corresponding point of view.

To confirm this experience, let us experimentally select a particular interconnection of the activities concerned and let us show to what type of isomorphy of consciousness its model leads.

14.12 Isomorphy of Consciousness in Inanimate Systems

Let us assume a mechanism working as follows:

The organism first creates certain images which mutually combine in various ways. The resulting image gives rise to a stimulus on the basis of which, for instance, the organism gets up and leaves the room, or pronounces some sentence, etc. What we shall then regard as essential for this mechanism is, that the organism always first produces some image (no matter whether due to the impulse of some distinct percept, or as the resulting image of its constructive imagination, or as an image freshly recalled from its memory). This image then becomes the stimulus upon which the organism builds its further activity. This image, as well as the stimulus by which it acted on the organism, are retained together with the present activity in the memory of the organism so that this organism will later be able to recall this whole process from its memory as its own mental image. We are thus concerned with a record which can be recalled under certain conditions suitable for this purpose.

It will now be very easy to show that such a mechanism can be modelled in an inanimate system. First of all we must base ourselves, in accordance with the principles of modelling, on a suitable mapping. Let us take the required definitions of mapping from the list in Sec. 14.5. Rewriting the foregoing paragraph according to this list, we obtain the following (compare the individual sentences):

For this mechanism (the mechanism of the isomorphy of consciousness) we regard as essential that the digital computer always first produce some result in the arithmetic unit (no matter whether on the basis of an input signal transformed by the input program, or as the final

result of the operation of the arithmetic unit, or as signals extracted from the store without any adaptation). This result is taken over by the control unit, which derives from it the instruction whereby it controls the further activity of the computer. The result, as well as the instruction derived from it, together with the present activity, are then inserted in the store so that the computer will later be able to recall this whole process from its store and to reproduce it in the arithmetic unit.

Let us for a moment call (even though not in accordance with the terminology of psychology) the action proceeding in this way an experience. The isomorphy of the described type of consciousness in an inanimate system has then the property that the system not only acts on the basis of an image (a representing image) prepared in advance, but that it is also capable of later recalling every experience of this kind, and thus to describe it later when requested to do so (e.g. in conversation), i.e. to go on using it.

In this model we used, for purposes of mapping, the list given in Sec. 14.5 which, however, is open to criticism. We should therefore like to remind the reader that there is no need to see the seat of imagination always in the arithmetic unit, i.e. to consider the mapping given in the list as the only possible one. This list only gives a certain viewpoint from which we then performed our experimental comparison. On the other hand we must realize that a comparative list set up arbitrarily might lead to considerable difficulties in the interpretation of some further accompanying phenomena, i.e. it might narrow down the viewpoint from which the corresponding comparison would make sense. We believe that our list permits not only a very wide interpretation of the behaviour of a computer as compared with the behaviour of living systems, but that it can also be used without alteration in models that are – for the time being – as inaccessible as, for instance, the isomorphy of consciousness.

Finally, it will be necessary to confront various definitions of consciousness. Let us assume that a certain definition of consciousness, denoted as definition Q, comprises concepts such as mental image, attention, x, y, z, etc. It links these concepts to each other, similarly as the definition of hallucination ties together such concepts as percept, image, wrong interpretation, etc.

The following now applies: In an inanimate system there is no sense in speaking of the isomorphy of consciousness according to definition Q unless, for the system in question, it is possible to define concepts such as image, attention, x, y, z, etc. Moreover, it must be possible to establish a mapping between the parts and properties of the organism (and according to the purpose for which this isomorphy is set up, e.g. a mapping of the pertinent logic planes of the concepts used) to which definition Q relates on the one hand, and the representing system on the other hand. Again, this mapping must make sense with respect to the viewpoint from which it is carried out, as well as with respect to the observer who interprets the behaviour of the system from the same point of view. There is perhaps no need to add that the mapping must be established not only between the concepts, but also between their links.

A representative consciousness according to definition Q can be spoken of only in an inanimate system which statisfies the following assumptions:

1. On this inanimate system it is possible to define image, attention, x, y, z, etc. (i.e. to establish, by means of a mapping, the representing image, representing attention, etc.), that is the concepts contained in the definition.

2. The definition of consciousness Q, transformed according to the mapping performed in this manner, expresses the actual behaviour of the corresponding inanimate system within the full range of definition Q.

14.13 Can an Inanimate System Become Aware of Itself?

Let us perform the following mental experiment: Let us equip a digital computer, possessing an isomorphic consciousness, with the facility of formulating in human language the work performed by the control unit. This can be done with practically every digital computer by setting up a special program for it. Now let us adapt this behaviour so that, when the computer performs an instruction taken over by the control unit from the arithmetic unit, it will report on this activity in the first person. For instance, the control unit issues an instruction to read a punched card by means of the corresponding card reader, and says

(writes out on a typewriter, etc.): "I have made up my mind (i.e. I have prepared this by means of the arithmetic unit) and on this basis I have taken the next card". At some other time, it issues an instruction to print recordings from the magnetic tape, and says: "I have decided to write out the text stored in this or that part of the memory".

In case of actions stimulated by the control unit without having prepared them in advance in the arithmetic unit, but where the control unit obtains a signal that they have been performed, let it pronounce: "I have done this without previous consideration".

Finally, when we are concerned with instructions which have not been stimulated by the control unit (no matter whether these instructions are contained in the program or have arisen owing to some defect), but where the control unit is informed by its control circuits that these instructions have been carried out, let it pronounce: "This is being done by my 'body' or 'my system' by itself, but I am not responsible for it".

We thus arrive at a very interesting situation, when the computer behaves

1. as though it were aware of itself,
2. as though it were capable of self-observation,
3. as though it were capable of distinguishing between what it does of its own will and what is forced upon it (i.e. what it is incapable of affecting),
4. as though, in case of a defect, it had the impression that certain defects were introduced not by itself, but by some other agency.

The experiment described, which to-day is quite conceivable in reality, can be very interestingly modified or enlarged in many respects. Does this experiment not remind ourselves very suggestively of human behaviour in certain instances? Of a behaviour of which, similar to the computer, we cannot make sure whether its manifestations do or do not correspond to actual subjective experiences of the pertinent system?

At the present we cannot yet say much about whether an inanimate system can be aware of itself in a manner similar to man. One thing, however, is certain: To-day we are already capable of establishing in an inanimate system a behaviour in which it will quite convincingly exhibit a "consciousness of itself".

CHAPTER 15

LANGUAGE AS A MEANS OF COMMUNICATION BETWEEN MAN AND MACHINE

15.1 INTRODUCTION

We concluded Chapter 13 with considerations involving language as an instrument for the transfer of proper models from one system into another. When using language for communication, we note whether the person to whom we talk understands what we say. Thus, the object of our investigation in this chapter is the question of what we mean by "understanding" a given text (written, heard, read, etc.), especially when the system which is to understand the text is inanimate.

We want to contemplate the question of what can be gathered from a particular text when disregarding the sense of the individual words, i.e. of what is determined in the text by its formal, e.g. grammatical aspects and what may be expected from its full utilization. We certainly feel that we cannot expect a machine to understand, as things are at present, individual words as we understand them. We are therefore interested in the degree to which a machine can answer our questions, and from which viewpoint and to what degree it can "understand" the given text so as to permit us to communicate with it, without the machine knowing the meaning of the words.

The problem of communication with a machine by means of our language is not only very interesting, but also highly topical. At the present we can speak with a machine only in its own language. We must put our questions in the form of its instruction code, and present problems to it only in the form of a program, etc. For instance, we have no possibility of explaining to the machine that a particular fault in its operation occurred due to this or that reason, and that it could avoid this fault in the future by taking, under certain circumstances, a different course. At the same time we feel clearly that, if we could use normal language for communicating with the machine, our situation would in this respect be greatly simplified.

Similarly, we are interested in the problem of whether and under what circumstances it would be possible to explain something to a machine by using an example so that the machine would learn its lesson from it and later correctly apply whatever we explained by means of the example (see Sec. 15.19).

We are just as much interested in learning to what extent a machine is capable of abstracting the contents of a given text (Sec. 15.22), arranging it stylistically (Sec. 15.23), etc. Such are the questions we want to answer in this chapter so as to clarify our basic approach to the problem and give the reader a clear picture of the linguistic questions and types of machine operation involved. We also want to show which of the results can already be regarded as immediately applicable, and which questions remain as yet unsolved. Because of the restricted space available, we shall avoid all explanations not immediately concerned with the problem of verbal communication between man and machine.

What, in our opinion, is the practical applicability of the answers to the questions raised? We see it, for instance, in the possibility of accumulating the most varied pieces of knowledge, nowadays published in great amounts in papers, treatises and books. To avoid searching in the literature when doing scientific work or treating for some other purpose all sources directly from the individual papers, abstracts are published in special periodicals, where the reader finds the contents of individual papers which have appeared in different journals. When elaborating a given theme, we first look up those papers whose contents seem to indicate that they fall within our sphere of interest. Only after studying the papers thus selected we learn from some of them what we were really interested in.

This kind of work is very exacting and consumes much time. We therefore ask: Can a machine do this kind of work for us, or will some machine be capable of doing so in the future?

Secondly, let us note in what way man acquires his knowledge, for instance when studying at school. The university student obtains some literature dealing with a particular subject, for example the design of power supply units using transistors. The student reads the literature relating to the matter and attends the relevant lectures. In both cases he acquires information. However, in order to be later able to answer va-

rious questions concerning this particular subject, it is not sufficient to remember this information – he must also understand it. For instance, he cogitates as follows: I have to design a power supply for a voltage of 24 V and a current of 6 A. How will the individual components have to be connected in the circuit? What will be the values of the individual resistors and capacitors? What types of transistors will I have to use? What else do I have to know about these power supplies if I am correctly to decide among several possible solutions?

The student does not obtain the answers to these questions at the lectures, nor are they given in the relevant literature. If he is to know what to do, the student must have understood the lectures attended and the literature read to such a degree as to be able to derive direct answers to the questions on the basis of his own knowledge. It is clear that the usefulness of computers for facilitating our work would be immensely enhanced if we knew how to present texts to the machine in such a manner that it would be able to "learn" them so as to be later able to answer our inquiries correctly.

15.2 Can a Machine Understand Our Language?

If we say that we understand something, this statement may interest us from two points of view: First from the viewpoint of our mental images and, possibly, our experiences, secondly from the viewpoint of our future behaviour.

A person who observes us while we listen to some explanation has no means of knowing whether we really understand what is being explained to us. He will only know whether we expressed our assent. This assent, however, cannot be conclusive for his final judgment as to our comprehension. How is he to make sure? He can do so, for instance, by putting questions to us. He will be convinced of our having really understood the explanation only if we give the correct and appropriate answers.

Another means of making sure whether some system correctly understood an explanation is by observing, how its behaviour changed after having obtained the explanation. For instance, some other person explains to us that the shortest path is not the one we are using, but some

different one. If we next time take the new path, he will declare that we understood his explanation because we changed our behaviour in the appropriate manner. However, if we persist in using the old path, he will suppose that we did not understand his explanation.

The reader is certain to have noted that what we call "*understanding a verbal explanation*" consists of three parts:

1. A verbal explanation must be given, received by some person. This person will be called the listener; when speaking of an inanimate system, we shall use the more general term "*listening system*".
2. The explanation must cause such changes in the listening system that it will be able, in a suitable situation, to evolve new reactions or change its previous reactions.
3. If a decision is to be made whether the system understood the explanation correctly or not, there must be somebody who can assess the behaviour of the listening system.

In this part of the book we shall deal with the question of whether a machine can also play the role of a listening system, in other words whether a machine can understand what we communicate to it by means of words. In agreement with the three points listed above, we shall further assume that:

1. The verbal explanation is imparted to the machine, for instance, by an electrical typewriter or by a device capable of reading printed texts.
2. It is not sufficient for the text to be stored in the memory of the machine, since its task will be not only to recall it, but also to answer various questions with the aid of this text. How the correct reactions (answers) of the machine are prepared on the basis of the inserted text will be the subject of our further explanation.
3. We will be the ones to decide whether the machine correctly understood the inserted text. Our decision criterion will be the correctness of the answers given by the machine. Thus, we shall not relate "understanding" to what happens inside the machine (figuratively speaking, to its subjective experiences), but how the machine behaves externally (towards ourselves).

If all the answers of the machine are such that they correctly follow from the inserted text we shall say that, in the sense of modelling, the machine has understood the text.

It now remains to define what we mean by saying that the machine understands the given text.

Definition 1 (understanding of text by machine): *A machine understands a text if it gives correct answers to questions whose answering follows from the text.*

The definition given in this way is suitable for assessing only certain cases (see the conclusion of this section). It may happen, however, that several texts have already been presented to the machine. When inserting another text, we would like the machine to seek its answers not only according to the latest text, but also from the previous texts. In such a case its answers might be more comprehensive since it would have the chance of looking for relationships on the basis of knowledge acquired previously. Figuratively, we might then speak of the intelligence of the machine. We relate the term "*machine intelligence*" to the fact that the machine already possesses a store of knowledge acquired from texts inserted previously, which it utilizes for answering questions presented to it. Again, we intend to use "machine intelligence" as a technical term in the sense of modelling, and not as though we wanted to equate internal processes in man and machine.

This consideration leads us to the following modification of the definition proposed above:

Definition 2: *A machine understands a text if it gives correct answers to questions whose answering follows from the given text on the one hand, and from its prior store of knowledge on the other hand.*

The term "correct" in this definition means, that the answers will be assessed by us and that we shall judge them subjectively from our point of view, i.e. according to our own ideas concerning correctness. The reference system relative to which the correctness of the answers will be judged consists thus of ourselves, our knowledge and our logic.

The above definition is still not quite satisfactory, although it has been expanded with respect to our preceding attempt. It may happen that the machine correctly relates the knowledge, resulting from the

new text, to its prior knowledge, but that the questions put to it cannot be correctly answered on the basis of all this knowledge alone. In this case it would therefore be wrong to assume that the machine does not understand the text because it does not give the correct answers or cannot answer at all. Here, we cannot base our judgment merely on the external manifestations of the machine. The essential basis for understanding will be that the machine, when faced with the new text, "correctly links up its new with its prior knowledge". Questions put to the machine must then be regarded as forming only a means by whose aid we make sure that the aforesaid relation has been correctly established. However, questions and answers are the only means of ascertaining that the machine understands (i.e. correctly links up) the text, if we want to keep the machine intact. We are here in a situation quite similar to that encountered when explaining something to a human being. The only chance of ascertaining whether he has correctly understood is to put various questions to him and to draw the corresponding conclusions from the answers given. If the text presented is not in the form of orders or does not concern something which the machine is to do – even though after complicated "considerations" – it is of no avail to observe reactions of the machine other than answers.

Based on the preceding considerations, we can now modify our definition of understanding as follows:

Definition 3: *The machine understands a text if it links up the knowledge resulting from it with its prior knowledge in the correct manner.*

This definition will be suitable for cases where we want the machine to answer our questions on the basis of all its knowledge. On the other hand, in cases where we are concerned with answers given on the basis of a single text, or on the basis of a distinct limited group of texts, we shall use the first definition. The second definition of understanding is suitable for cases where we want to make sure by means of questions, whether the prior and the newly inserted knowledge is sufficient for the machine to answer questions of a particular kind. If the answers of the machine are correct according to the second definition, we shall say that the prior store of knowledge ("intelligence") of the machine is satisfactory for our questions at the given stage.

15.3 WHAT IS THE MEANING OF THE TERM "UNDERSTANDING" FROM THE VIEWPOINT OF THE MACHINE?

For a full explanation of the term "*understanding*" we must add that it need not always be referred to a verbally expressed relationship. It is known that we are capable of communicating by various other types of signals. In order to include cases where the relevant information is not transmitted verbally, we can generalize our former definition of "understanding" as follows:

The machine understands the given signal (set of signals) *if it adequately changes its former behaviour as a result of having received it.*

The term "it adequately changes its behaviour" is intended to mean that the machine has evolved new reactions to certain signals, or has changed its former reaction to such signals or, finally, has prepared conditions for establishing new reactions in the future, all that in agreement with the point of view from which we assess its behaviour. The definition formulated in this manner applies to any type of signal received. The correctness of understanding is again judged relative to some reference system, this fact being expressed by the word "adequately". It is clear that the definition also applies to information expressed verbally.

In addition, let us note that the definition of understanding does not apply to signals which, although stored by the machine in its memory and – possibly – recalled, do not affect its behaviour. Finally, we must realize that signals on the basis of which the machine changes its behaviour are of importance to it by enriching its behaviour. They enlarge its former store of knowledge or, as we said before, increase its intelligence. Therefore every signal which is understood by the machine is said to have a certain significance or content, which we call information. Such a signal thus brings information to the machine. So as to be able to use this term with greater accuracy, let us define it as follows: *Only signals understood by the machine can be considered to carry information for it.* In this definition we ascribe to the word "information" a relative meaning linked with the words "for a machine". At the same time we ascribe information (from the viewpoint of the machine) to every signal which causes a change – even if delayed – in the behaviour of the machine.

According to this definition a signal repeated several times in succession without evoking new states in the machine does not constitute information with respect to the machine. This is exemplified by the following situation: The first signal arriving causes the machine to adequately change its behaviour. If the same signal arrives later again, under such conditions that it effects no change – either immediately of subsequently – in the behaviour of the machine (which already experienced a change due to such a signal), then the second equal signal does not present anything new to it. Since, in consequence, the machine no longer changes its behaviour, we do not consider the second signal as carrying information for the machine. Because this signal does not affect its behaviour, we cannot even speak of the machine having correctly understood it. The machine can only be said to have received the signal.

However, the situation may develop as follows: On receipt of the first signal, the machine modifies its behaviour so that it can be said to have correctly understood the signal. Before, however, the same signal appears for the second time, other signals arrive which result in changing the prepared reactions as though the first signal had not been received at all. Then, of course, on arrival of the second signal, even though it is equal to the first signal, the behaviour is changed again. In this case the second signal is said to have brought new information to the machine. If the machine now again changes its behaviour in an adequate manner, it is said to have understood the signal. This is a case which can be described by saying that the machine "forgot" the first signal under the influence of the other signals.

It will be seen that we must exercise great caution in our considerations as soon as we start dealing more profoundly with concepts such as understanding, information, adequate reactions, etc. When using these terms it is therefore important to ascribe to them always precisely the same content which we originally adopted for them.

15.4 The Text as a System

In the sections to follow we shall turn our attention directly to the problem of the understanding of language and to its use. In order to be able to deal with a complete whole always as with a system, every

verbally expressed whole will be called a text, no matter whether written down or presented orally.

According to our former explanations, a text determined in this manner constitutes a system.

This is a symbolic system whose elements are words and whose connections form the most diverse links, which will be spoken of as grammatical relations, syntactic relations, inter-sentential relations, etc.

When dealing with this system it is of special importance to realize what is meant by the input.

Input and input signals are the questions presented to the text, output and output signals are the answers offered by the text.

More detailed considerations will show that, so as not to come into conflict with concepts defined before, *concrete words used in the question must be regarded as input signals, whereas the grammatical form of the question must be regarded as the input.* When pronouncing a sentence which supplements the text, we are concerned neither with input signals nor with the input. However, if we present some sentence in the interrogative form and seek the answer offered to this sentence by the text, we are concerned with input signals influencing the text (i.e. the system under investigation). This situation is peculiar in that the input cannot be localized, as opposed to the case when we speak, for instance, of the input of some living system being its organ of sight, hearing, etc. Despite this fact, our conception of the text as a system is not opposed to the definitions of a system and its behaviour as presented before.

It has already been said that we regard as the input anything that can be defined as an input, without having to localize it. For instance, let us observe the behaviour of a small ball suspended on a chain inside a motor car from the viewpoint of the action of both the centrifugal force and terrestrial gravity. The system thus defined – the suspended ball – has from the viewpoint of our observation two inputs, namely terrestrial gravity and the centrifugal force. The input signals are, first, the magnitude of the gravitational force which – as we know in advance – will not change in the course of our observation and, secondly, the magnitude of the centrifugal force which will depend on the speed of the vehicle on curves, etc. Neither of these input signals will act on the system

under observation – the small ball – in a single defined place, but will act on all the molecules of the ball, both inside and on its surface.

Similarly, in a text we consider as the input the grammatical aspect of the question which "acts" upon the whole text or on some of its parts, whereas its concrete contents in the form of individual words are regarded as input signals, similar to our regarding the concrete magnitude of the centrifugal force acting on the small ball as input signals. The input and stimulus of a text is thus the question presented to it. Similarly, *its output will be represented by the sentence or system of sentences called the answer, the concrete contents of these sentences being regarded as the output signals.* Thus, only that sentence which answers the given question is considered to be the output, and not just any part of the text, a distinct word of the text, or some arbitrary sentence. Similarly, not every manifestation of a system, but only its output signal can be regarded as the response to a stimulus applied to it.

In order to be able to enlarge upon the problem in an effective manner, let us devote the following sections to an exposition of the necessary definitions.

We have frequently invested expressions, already used before, with a new meaning because we did not feel sufficiently competent to introduce entirely new concepts right at the beginning of our explanation of these very complicated problems. We believe that the use of kindred terms will help to elucidate the intended approach and will serve as a stimulus for the later introduction of new terms, based in addition on complementary aspects introduced by other authors.

15.5 GRAMMATICAL RELATIONS

Henceforth, we shall consider as a *grammatical relation* every relation expressed by a rule R which can be applied quite formally to the determination of relationships in the text under investigation. An example of such a relationship can be a relation expressed by grammatical rules. Grammatical relations may be concerned with connections between individual terms of the text under investigation. However, these may also be relations between groups of terms expressed, for instance,

by parts of sentences or whole sentences. We may also be concerned with relations between entire passages of the text, etc. The substantial criterion of a grammatical relation is that it can be determined by a purely formal application of the rule defining it. As such we also consider a rule or a group of rules which determine under what conditions some other rule applies and what the exceptions are. In a similar manner, we also include here tables of synonyms, i.e. words identical in sense, if available when examining the text. To be more accurate, when such a table is available we use it according to rules which determine that certain terms of a text may be interchanged. Things are similar when applying our knowledge of the hierarchy of words. We know, for instance, that the dog is an animal. If a table is available (in the case of a machine it may be a table, for ourselves it is either our store of knowledge no matter how acquired, or a suitable dictionary used in case of necessity) which quite formally determines the hierarchy of words, e.g. which concept is superior to the concept "dog", this table is also included in the formally used rules R.

15.6 GRAMMAR AND ITS MISSION

The concept of *grammar* will be understood to mean the set of all rules expressing grammatical relations in the sense described above. In grammar we are thus concerned with an accepted set of rules which enable two different individuals using this grammar to determine in the same manner all the grammatical relations in a particular text written in accordance with this grammar.

We assume, of course, that the grammar is constructed consistently and uniquely, i.e. that the rules do not contradict each other and that the correct application of any rule (under conditions satisfying this rule) always leads to the same result.

If several individuals accept the use of the same grammar, their communication by language becomes easy (assuming the same vocabulary). Owing to the common rules, their mental images evoked by a common vocabulary are grouped in the same manner when employing language. For example, when using a verb in the active voice, the action indicated

by the verb will be attributed by these individuals to the subject and not to the object, etc. Grammar thus constitutes for the user of language a built-in set of rules according to which he will deal with the words received, which are images coded according to a common code – the vocabulary (see Sec. 13.7).

15.7 Restrictions on the Exclusive Use of Grammar

Grammar (according to the definition given above) permits a particular text, written in accordance with it, to be analysed. On the basis of this analysis it is possible to determine a number of relationships resulting from the given text. For instance, if the text contains the sentence "*A white house stands at the edge of the green forest*", grammar enables us to determine unequivocally that the house of which we speak is white and not green, that the forest mentioned in the text is green and not white, etc. Such statements follow unequivocally from the fact that the person who constructed the text used the same grammar as the person who reads it. If each of them used a different grammar, the reader might very easily – even if applying the correct procedure – arrive at incorrect conclusions (i.e., at what we usually call a misunderstanding).

Grammar is suitable only for determining grammatical relations in the text. No other relations can be determined on the basis of grammar.

This statement, which sounds in our explanation as self-evident, is not always considered as such when encountering complicated texts, where we presuppose the knowledge of further conventions not related to grammar. To ensure correct treatment of the text, we must therefore carefully distinguish between grammatical relations and relations of other types.

15.8 Extra-grammatical Relations

Relations, the knowledge of which is automatically presumed when in contact with some other individual, are also included in extra-grammatical relations. For instance, when saying "*Paul's mother*

had a fall yesterday" we assume that the mother is a woman whose son is Paul. If the grammar employed does not comprise a rule saying that "mother is a woman" and that the statement "somebody's mother" implies that we are concerned with a son, daughter, child, then this relation is not determined by this particular grammar and we know it from elsewhere.

To facilitate communication by language, common conventions are very frequently used, if possible by all those employing the common language. These conventions are usually not included in the grammar. If not all those using the common language are acquainted with these conventions, frequent misunderstandings or long-winded explanations result (for instance, nowadays in cybernetics).

15.9 COMMUNICATION OF EXTRA-GRAMMATICAL RELATIONS

Now let us note that extra-grammatical relations are very frequently communicated by an elaborate grammatical apparatus. The newly communicated relations are expressed by sentences, texts, conversations, etc. If we accept them as valid, we employ them and simultaneously presume them to be generally known.

For the sake of completeness we should add that language is not the only means of communicating certain relations. Music, various sounds, gestures, pictures, mathematical symbols, chess notation, chemical formulae and other means can serve this purpose just as well. In our explanation, however, we shall confine ourselves purposely to language only.

The use of extra-grammatical relations is governed by other than grammatical rules. It is therefore necessary to define, prepare and accept this new system also, and accordingly to deal with the given or presumed relations. This type of relations, their determination and use, do not fall into the sphere of grammar as defined for our purposes. They concern rather the acquisition of knowledge and its treatment in a sense similar to that spoken of at the end of the introduction to this chapter. We are not going to deal with this type of relation in greater detail.

15.10 Syntax, Syntactic Pairs, Syntactic Graphs*)

Information is communicated with the aid of language in formations called sentences. From the viewpoint of the branch of linguistics called *syntax*, the sentence is made up of so-called *sentence elements*. These enter into relations which are referred to as syntactic pairs. In every pair one element is always the main, and the other the dependent element. For our further exposition we shall need a more con-

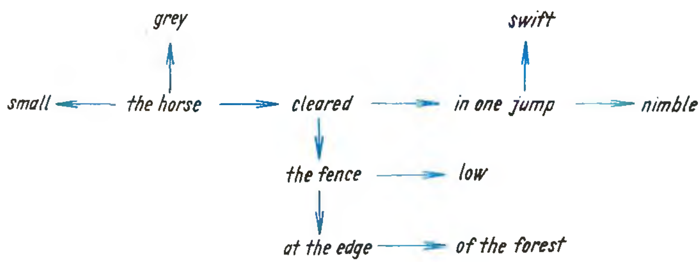

Fig. 15.1. Syntactic graph of sentence x: The small grey horse cleared the low fence at the edge of the forest in one nimble, swift jump

crete idea of the arrangement of words in the sentence on the basis of sentence pairs. This is why we shall make use of a graph to record sentence pairs. Fig. 15.1 shows the *graph of syntactic links* of the following sentence, denoted by x: "*The small grey horse cleared the low fence at the edge of the forest in one nimble, swift jump*". Syntactic pairs are indicated here by arrows. The sentence element at the beginning of every arrow is the main element, the element at the end of the arrow is the dependent element. The word "*horse*" is the main element of three sentence pairs.

*) Editorial notes:

1) We are concerned here with a conception of syntax generally in use in Czechoslovakia (especially in school tuition), which naturally is only one of the many conceptions existing in linguistics.

2) Some apparent inconsistencies occurring in this and the following sections arise from the fact that the deductions referring to Czech in the original are applied to English in the translation. It has only partly been possible to overcome the differences in structure between the two languages by modifications of the text.

The word "*jump*" occurs in one pair as the dependent element ("*cleared ... in one jump*") and as the main element in two other pairs ("*nimble jump*" and "*swift jump*"). The number of arrows here expresses simultaneously the number of all sentence pairs in the sentence. There is a total of ten in our example. As we shall in future often make use of such

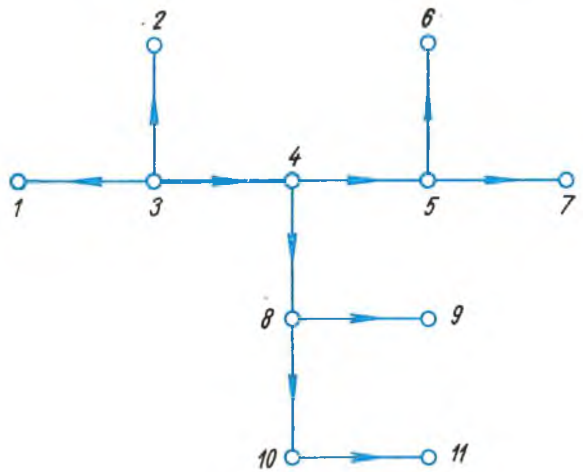

Fig. 15.2. General graph of syntactic links of sentence x: The small grey horse cleared the low fence at the edge of the forest in one nimble, swift jump

graphs, let us introduce the following assignment: we shall assign each sentence element to a *node of the graph*, and the relation between two elements of a syntactic pair to an *oriented connecting line*. These connecting lines will always be oriented, even if this is not expressly stated further on. This means that we shall always assume them to lead from the main to the dependent element.

The subject of the sentence is not dependent on any other part of the sentence. All arrows always point away from the subject. This is why we shall call it the main node of the graph. If we plot the graph of the abovementioned sentence in the form of nodes linked by oriented connecting lines without regard to the particular word which forms the content of the respective node, then we obtain a graph expressing the syntactic links

in the sentence in a general form. This graph – which we shall call the *general graph of syntactic links* – is shown in Fig. 15.2 for the example given above. To make the graph more clearly understandable, the connecting line between the subject and predicate (simple sentence) as one of the syntactic pairs is printed more heavily. The subject is at the beginning of the connecting line, the verb at the end according to the direction of the arrow.

Thus, *the graph of syntactic links is a graph whose nodes are formed of all sentence elements of the respective sentence and whose oriented connecting lines connect all syntactic pairs in the direction from the main to the dependent element.*

The general graph of syntactic links is a graph of syntactic links whose sentence elements are replaced by unnamed nodes.

15.11 Enlarged Node and Enlarging Branches

When observing the graph of syntactic links we find that individual arrows always point in the direction away from the main node. If several connecting lines depart from one node, then we say that several *branches* emerge from the node. Thus, in the graph of Fig. 15.2 three branches leave node 3, two branches leave node 4, one branch leaves node 10, and no branches leave node 1. All further connecting lines linking up with lines directly emerging, together with the corresponding nodes, are then considered as branches. In Fig. 15.2 for instance, two branches issue from node 4, one of them consisting of the nodes 5, 6 and 7 with their connecting lines, the other of the nodes 8, 9, 10 and 11 with their connecting lines.

Any node of the graph may be called an *enlarged* node. The branches emerging from it are called enlarging branches. For instance, if we declare node 8 in Fig. 15.2 to be an enlarged node, the branches containing the nodes 9, 10 and 11 will be its enlarging branches. If we declare node 4 to be an enlarged node, the branches with the nodes 5, 6, 7, 8, 9, 10 and 11 will be its enlarging branches. Returning to the example of Fig. 15.1 and applying the syntactic terminology introduced above, our

preceding statements will read as follows: The enlarging branches of the sentence element "*fence*" will be "*low*" and "*at the edge of the forest*". The enlarging branches of the sentence element "*cleared*" will be "*in one nimble swift jump*" and "*the low fence at the edge of the forest*".

The *enlarging branch* forms a part of the graph, called the sub-graph. For our example, the enlarging branches are illustrated in Fig. 15.3. Part a) contains the enlarging branch of node 8, part b) the enlarging branches of node 4.

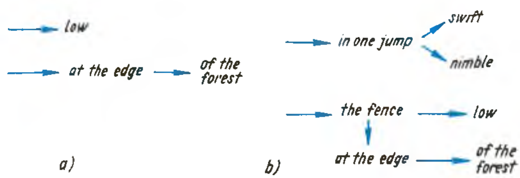

Fig. 15.3. Enlarging branches of the sentence elements according to the example illustrated in Fig. 15.1

a) Enlarging branches of the element "*fence*".

b) Enlarging branches of the element "*cleared*".

15.12 Semantic Structure of the Sentence and the Graph of Semantic Structure

A dependent element of a sentence pair can always be introduced by an interrogative word (mostly an interrogative pronoun). The interrogative word expresses in a certain manner the kind of link between elements of a sentence pair. It determines how the main element of the pair is related to the dependent element. For instance, in the pair "nimble jump" the interrogative words "what kind of" express the kind of jump. In the pair "at the edge of the forest" the interrogative words "of what" ("whose") express the "owner" of the edge, etc. There are relatively few interrogative words in our language. They therefore permit the types of link to be divided in a simple manner into a relatively small number of classes. The class is ascribed to the entire sentence pair, so that every sentence pair can now be fitted into one of the relatively small number of classes. The classes group the pairs according to the link which we call, for our purpose, the *semantic link of the pair*.

As already shown, the number of semantic links between the elements of a sentence pair, expressed by interrogative words, is relatively small. The sum of semantic links in a sentence is called their semantic structure. We express the semantic structure of a sentence again by a graph, called the *graph of semantic structure*. The class of the connecting line, expressed by the interrogative pronoun (word) of the dependent element of the

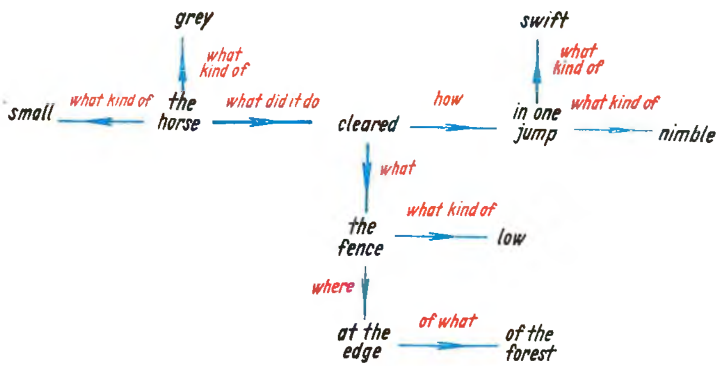

Fig. 15.4. The connecting lines of Fig. 15.1 supplemented by interrogative words

pair, is called the *weight of the connecting line*, in agreement with the terminology used in the theory of graphs.

Now let us again take sentence x as an example and let us supplement the connecting lines in Fig. 15.1 by the corresponding interrogative words. The graph modified in this manner is shown in Fig. 15.4. Let us now convert this graph into a general graph by omitting the sentence elements and replacing them by unnamed nodes. The result of this operation is shown in Fig. 15.5. The graph of Fig. 15.5 is the graph of the semantic structure of sentence x.

Thus, the *semantic link is a link between the elements of a sentence pair expressed by the interrogative word which introduces the dependent element and expresses the class of this link.*

The semantic structure of a sentence is defined as the set of all its semantic links.

The graph of semantic structure is a general graph of semantic links, where every connecting line has a weight corresponding to the class of the respective semantic link.

From the viewpoint of the theory of graphs, the graph of semantic structure is an oriented graph with weighted connecting lines, which form a tree with a unidirectional orientation of the branches from the fundamental node towards the terminal nodes of the branches.

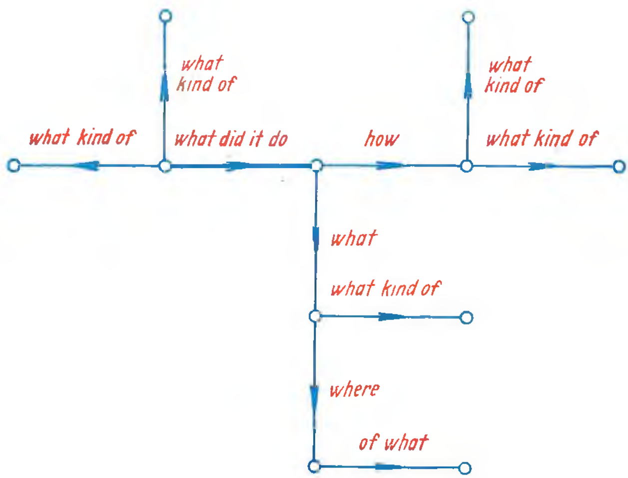

Fig. 15.5. Graph of the semantic structure of sentence x derived from Fig. 15.4

15.13 SUBORDINATE CLAUSES IN THE GRAPH

Subordinate clauses, regarded independently, can be converted into a graph in the same manner as described above. Considered together with the main clause, they will be seen to enlarge some of its sentence elements. To avoid difficulties when constructing the graphs, when describing them and, especially, when converting them into a machine language, i.e. when coding them, it will prove of advantage to deviate in this case from linguistic usage.

Fig. 15.6 shows the graph of syntactic links of a sentence denoted by *y*: "*The fine silver veil fluttered from the shoulders of the dancer as if a sum-*

mer breeze were blowing the shadow of clouds away from the white town, and came to rest on the dark ground". The graph of Fig. 15.6 is constructed, for purposes of comparison, according to linguistic usage, i.e. in a manner we are not going to use. The subordinate clause "as if a summer breeze were blowing the shadow of clouds away from the white town" is connected here to the main clause by the pair

$$\rightarrow \textit{fluttered} \rightarrow (\textit{how?}) \rightarrow \textit{as if blowing away} \rightarrow .$$

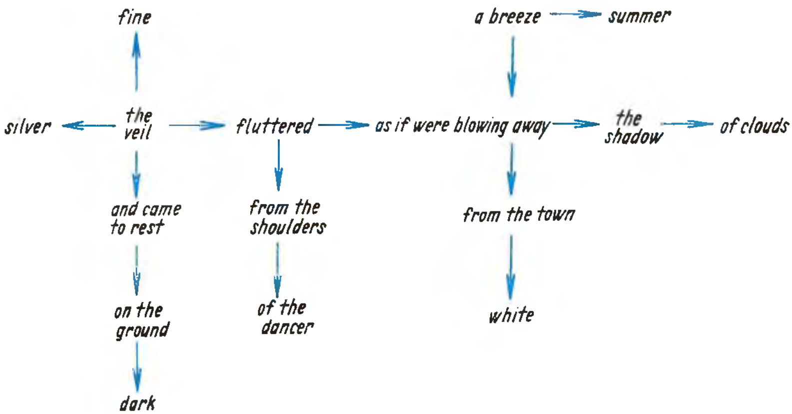

Fig. 15.6. Syntactic graph of sentence y: The fine silver veil flutered from the shoulders of the dancer as if a summer breeze were blowing the shadow of clouds away from the white town, and came to rest on the dark ground

In this case two arrows point towards the node "*as if blowing away*", violating the rule according to which all connecting lines of the graph are oriented outwards from the main node. The method to which we shall consequently adhere is illustrated in Fig. 15.7. Here, the subordinate clause is attached by the pairs

$$\rightarrow \textit{fluttered} \rightarrow (\textit{how?}) \rightarrow \textit{as if} \rightarrow (\textit{who? what?}) \rightarrow \textit{a breeze} \rightarrow .$$

From the linguistic point of view, the node "*as if*" cannot be considered as a sentence element. We therefore call it an intermediate element. This newly introduced element permits us, on the one hand, to retain the weight of the connecting line (how?) which links the subordinate to the

main clause (without disturbing its grammatical sense and its content), and on the other hand to attach another connecting line, whose weight is the interrogative pronoun "*who*" ("*what*"), followed by the subject of the subordinate clause. Since, according to our conventions, all the connecting lines which start at the subject are oriented outwards, the whole graph acquires a uniform orientation.

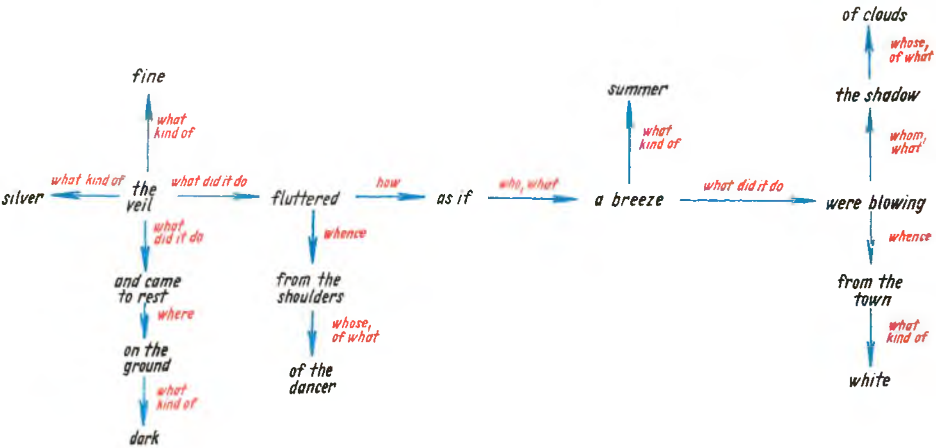

Fig. 15.7. Graph of syntactic links of sentence y according to the convention adopted

15.14 QUESTIONS WHICH INTRODUCE SENTENCE ELEMENTS

If we ask a question introducing some sentence element and construct the graph of semantic links of this question, we find that the question constitutes a sub-graph of the graph of the sentence to which our question refers. For instance, let a question concerning sentence *y*

Fig. 15.8. Graph of syntactic links of the question: Whence did the fine silver veil flutter?

be as follows: *Whence did the fine silver veil flutter*? The graph of this sentence is shown in Fig. 15.8. If we compare this with the graphs of Figs. 15.7 and 15.9, we find that the interrogative adverb belongs to a connecting line which, in our question, has no sequel. The question is

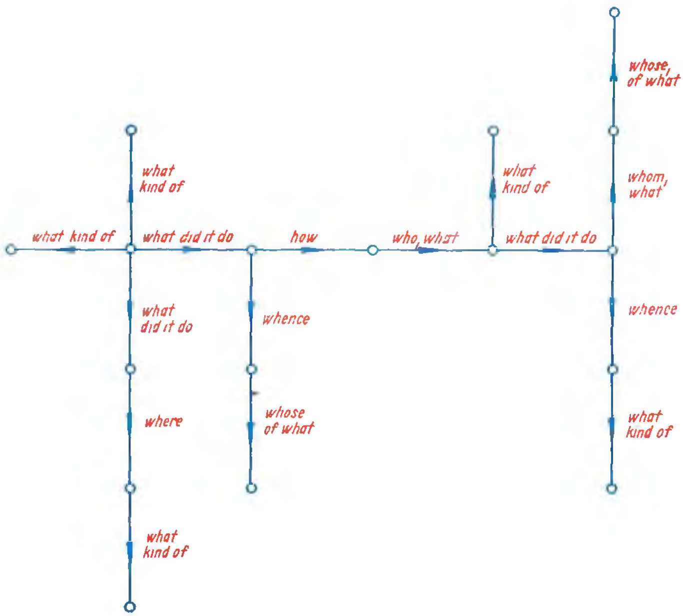

Fig.15.9. Graph of semantic structure of sentence y: this graph is common to the sentence z

answered by supplementing the corresponding unfinished branch of the graph. According to graph 15.7 we find that the answer is the branch "*from the shoulders of the dancer*", since it is this branch to which the interrogative adverb "*whence*" is pointing. Similarly, let us ask "*How did the fine silver veil flutter*?" We obtain the same answer as though we had asked "*How did the fine silver veil flutter from the shoulders of the dancer*?" The graph of this question is shown in Fig. 15.10 and comparing this with the graphs 15.7 and 15.9 we obtain as the answer the branch "*as if a summer breeze were blowing the shadow of clouds away from the white*

town". This is the sequel of the graph in the direction of the branch designated by the interrogative adverb "*how*?" The semantic structures of the two questions are illustrated in Fig. 15.11.

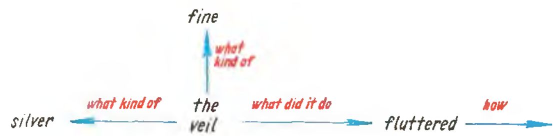

Fig. 15.10. Graph of syntactic links of the question: How did the fine silver veil flutter?

Fig. 15.11. Graph of the semantic structures of the two questions from Figs. 15.8 and 15.10

15.15 The Equal Semantic Structure of Two Sentences as an Analogy of the Two Sentences

If two sentences have the same semantic structure, one of them can be modelled by means of the other. It is sufficient in the graph of syntactic links to ascribe to each other the nodes belonging to the same node in the common graph of semantic structure.

As an example let us present sentence z: "*A sharp cold wind blew from the north of the country, as if a young shepherd were throwing clods of earth from the narrow path, and came to a stop at the tumble-down roof*", which has the same semantic structure as sentence y.

Fig. 15.12 shows the graph of the syntactic links of sentence z. If we compare this illustration with Fig. 15.7, we find that the equally placed connecting lines of the two graphs belong to the same class. The graph of semantic structure in Fig. 15.9 is thus common to both the sentences y and z.

Now let us go through one node after the other according to the graph of Fig. 15.9 and let us find for every branch the elements relating to the corresponding node. In this manner we obtain the allocation of sentence elements expressed in Table 15.1.

Table 15.1.

Allocation of the sentence elements of sentence *y* and sentence *z* on the basis of their syntactic links.

fine	*sharp*	*clouds*	*earth*
silver	*cold*	*town*	*path*
veil	*wind*	*white*	*narrow*
fluttered	*blew*	*came to rest*	*came to a stop*
as if	*as if*	*ground*	*roof*
breeze	*shepherd*	*dark*	*tumble-down*
summer	*young*	*shoulders*	*north*
blowing	*throwing*	*dancer*	*country*
shadow	*clods*		

Two sentences having the same semantic structure are called analogous. This analogy applies under the assumption that the individual elements are correctly mapped one with respect to the other, the mapping just described being considered as the correct one.

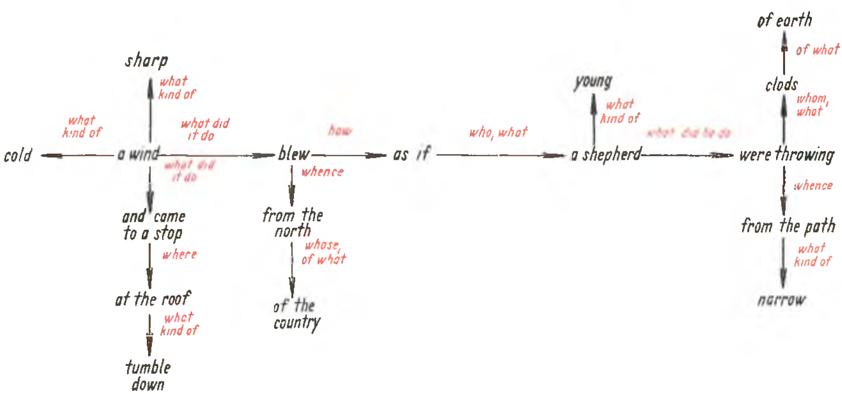

Fig. 15.12. Graph of syntactic links of sentence z. From a comparison with Fig. 15.7 it follows that sentence y and sentence z have the same semantic structure, expressed in Fig. 15.9

It may happen that the representation of individual elements is not unequivocal. For instance, in the sentences y and z, the mutual mapping may be performed in the following manner: *fine – cold, silver – sharp,* or, just as well, *fine – sharp, silver – cold.*

Since we have no additional reasons for preferring one type of allocation to the other, we consider both methods as equivalent and both analogies thus obtained as correct.

15.16 Intersection of Two Graphs

Let us consider the graphs of the semantic structure of two sentences. So as to produce an analogy of these semantic structures and, with their aid, of the corresponding sentences, it is of advantage to use

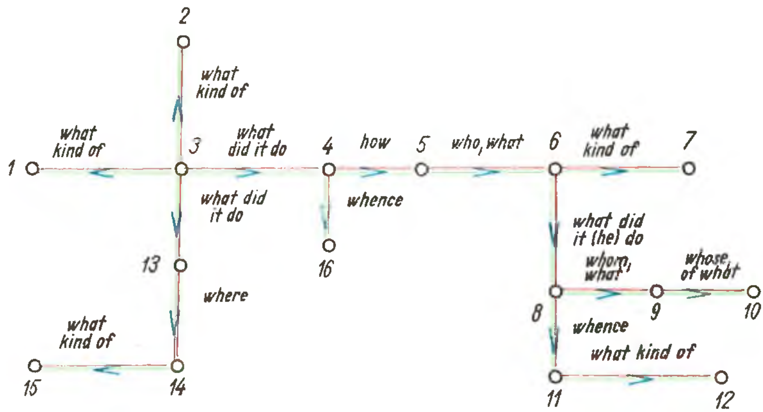

Fig. 15.13. Intersection of the semantic structures of sentences y_1 and z_1 according to Fig. 15.15

the *intersection of two graphs.* This intersection is a graph obtained by means of the algorithm described in Sec. 15.17. To facilitate tracing, the intersection of the semantic graphs of two sentences is illustrated in Fig. 15.13 in colours. These are the sentences y and z, slightly altered so that their semantic structures will not be quite identical. The resulting sentences are denoted as y_1 and z_1 respectively.

Sentence y_1: "*As if a summer breeze were blowing the shadow of clouds away from the white town, the fine silver veil fluttered from the shoulders of the dancer and slowly came to rest on the dark ground.*"

Sentence z_1: "*As if the black-eyed, strong shepherd were throwing a hard clod of earth from the narrow path, a sharp cold wind blew from the north as the last messenger of winter, and came to a stop at the tumble-down roof of the lonely house at the edge of the forest.*"

Fig. 15.14. Graphs of syntactic links of sentence y_1 and sentence z_1

Fig. 15.14 shows the graphs of the syntactic links of the sentences y_1 and z_1. Both graphs are supplemented with the interrogatory words corresponding to the connecting lines. When comparing the two graphs, we see that they are not quite identical. Fig. 15.15 shows the graphs of the semantic structures of the sentences y_1 and z_1 superimposed upon

each other according to the rules of the algorithm governing the intersection of two semantic graphs (Sec. 15.17). The identical parts of the two graphs represent the wanted intersection. Fig. 15.13 illustrates this intersection alone.

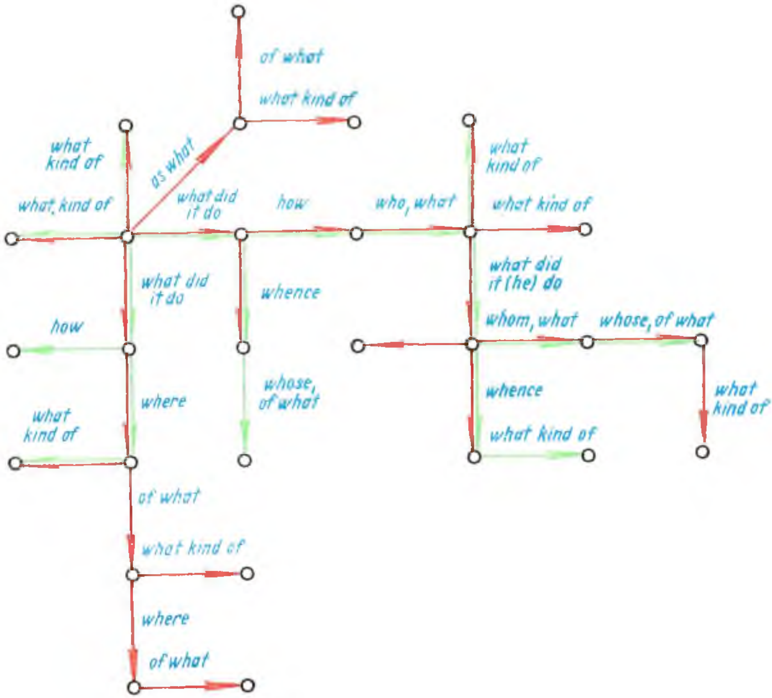

Fig. 15.15. Graphs of the semantic structures of sentence y_1 and sentence z_1 superimposed upon each other. The two-coloured connecting lines clearly show the intersection of the two graphs

15.17 Algorithm for Producing the Intersection of Two Graphs of the Semantic Structure of Sentences

1. Let us first determine the intersection of connecting lines starting from the main node. a) Connecting lines belonging to the same class are assigned to each other. These are the lines which belong to the

intersection of the two graphs. b) A connecting line belonging to one of the graphs, whose class does not occur among the connecting lines of the other graph, is not transferred to the intersection. Such a link, as well as the whole further branch which continues this connecting line, is no longer considered in this procedure.

2. Let us consider all nodes lying at the end of the connecting lines which have already been assigned to each other, i.e. the nodes already forming nodes in the intersection of the two graphs. Let us take one node after the other and let us determine for each of them the connecting lines which emerge from it and are of the same class. These form further connecting lines of the wanted intersection. Their terminal points form nodes in the graph of the wanted intersection. The connecting lines of a sentence whose class does not occur among the connecting lines of the other sentence are omitted, including the entire subsequent branch. If there appears the possibility of several different allocations of connecting lines of the same class emerging from a single node, all the possible allocations must be admitted as alternatives and used to conclude the algorithm.

3. The procedure of para.2 is repeated until all the connecting lines of the two graphs are used up. The common connecting lines of the two graphs obtained in this manner form – together with their terminal nodes – a graph which represents the intersection of the semantic structures of the two sentences.

15.18 Producing an Analogy of Two Sentences from the Intersection of Their Semantic Structures

Having obtained the intersection of two semantic structures (for instance in the form of a graph), we must now produce a correct mapping between the sentence elements in order to obtain our analogy. The mapping is performed as follows:

1. We assign those nodes of the two sentences to each other, which are contained in the graph of the intersection.

2. To each node of the first sentence we add all the corresponding branches of the first sentence which have not been used in the intersection.

3. To each node of the second sentence we similarly add all the corresponding branches of the second sentence, which have not been used in the intersection.

4. If several connecting lines of the same class emerge from some of the nodes of the intersection, we do not make any difference between the terminal nodes.

An example of such a mapping is given in Table 15.2 for the sentences y_1 and z_1. The rows in the table are numbered. The table contains the mutual mapping of the nodes according to the four rules given above (in accordance with the graphs of Figs. 15.13 to 15.15).

Rows 4, 9 and 15 of this table are examples for para. 1, rows 3, 11 and 16 for paras. 2 and 3, and rows 1 and 2 for para. 4.

Such an analogy of two sentences can be used for modelling the relations in one sentence with the aid of those in the other sentence.

Table 15.2.

Allocation of the sentence elements of sentences y_1 and z_1 on the basis of the intersection of their semantic structures.

1	*cold (sharp)*	*silver*	10	*earth*	*clouds*
2	*sharp (cold)*	*fine*	11	*path*	*town*
3	*wind as the last messenger of winter*	*veil*	12	*narrow*	*white*
			13	*came to a stop*	*came to rest slowly*
4	*blew*	*fluttered*	14	*roof of the lonely house at the edge of the forest*	*ground*
5	*as if*	*as if*			
6	*strong shepherd*	*breeze*			
7	*black-eyed*	*summer*	15	*tumble-down*	*dark*
8	*were throwing*	*were blowing*	16	*north*	*shoulders of the dancer*
9	*hard clod*	*shadow*			

The importance of the foregoing explanation to the treatment of texts by machines consists in that *the entire procedure of finding the* relevant *analogy between sentences takes place* quite *mechanically* according to rules whose application does not require any orientation by the meaning of the individual words. We are thus concerned with a method which can be applied by a machine to determine to what degree two sentences are analogous, and to produce this analogy on its own.*)

15.19 An Example of the Use of Analogy between Two Sentences for Answering a Question by Machine

A kind of narration in which another event is recounted instead of the actual one, for instance a parable, fable, a fictitious event, etc., is sometimes also called an analogy. The relations presented in the analogy are then transferred to the actual case on the basis of a mapping whose knowledge is usually presumed, or is given only in part, assuming that the rest will be guessed. Let us present here an example of the analogy between two sentences. From the viewpoint of modelling, one of them – sentence y_1 – is the modelled system which we assume to be inaccessible to us. If we want to put a question concerning some sentence element, we can use as the modelling system the sentence z_1 which is at our disposal and of which we have somehow learnt that it represents an analogy. The input and output mapping (see Chapter 5) is given in Table 15.2 which has been derived so as to make the analogy between the sentences applicable to the widest possible extent.

For instance, let us put the following four questions relating to sentence y_1:

1. "*What kind of veil fluttered from the shoulders of the dancer*?"
2. "*How did the veil flutter from the shoulders of the dancer*?"
3. "*Where did the veil come to rest*?"
4. "*How did the veil come to rest*?"

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*) Editorial note:
The author here omits certain problems the solution of which is today the subject of very extensive linguistic research (i.e., in the author's terminology, making sure that the machine will be able to find out by what question to ask after a given part of the sentence, etc.).

Since it is the analogous sentence z_1 which we want to use for answering these questions, we must first find the input mapping (see Chapter 5). In other words, the questions must be translated into the language of our analogy. For this purpose we use the mapping given in Table 15.2. According to this, the questions will read – after the transformation – as follows:

1. "*What kind of wind as the last messenger of winter blew from the north?*"
2. "*How did the wind blow from the north?*"
3. "*Where did the wind come to a stop?*"
4. "*How did the wind come to a stop?*"

These questions are then used for the construction of graphs (see Sec. 15.14). By means of the graph of sentence z_1 (the red graph in Fig. 15.14) we find:

a) The answer "*sharp, cold*" as the sequel to the graph of question 1.

b) The answer "*as if the black-eyed strong shepherd were throwing a hard clod of earth from the narrow path*" as the sequel to the graph of question 2.

c) The answer "*at the tumble-down roof of the lonely house at the edge of the forest*" as the sequel to the graph of question 3.

d) A comparison of the graph of question 4 with the graph of sentence z_1 shows that no connecting line marked "*how*" emerges from the node "*and came to a stop*" in the graph of sentence z_1. It follows that this sentence (i.e. this analogy) cannot be used as a basis for answering the given question.

It now remains to perform the output mapping i.e. to transform the language of the analogy back to the original language of the question. For this purpose we again use the mapping contained in Table 15.2. Accordingly, we find the following answers, based on the answers of our analogy according to a), b), c) and d);

1. "*fine, silver*",
2. "*as if a summer breeze were blowing the shadow of clouds away from the white* town",
3. "*on the dark ground*",
4. "this question cannot be answered".

Let us note another circumstance essential to the operation of a machine. In finding the answers by means of our analogy we made no use of the meaning of the individual words. We found the correct answers a) on the basis of the mapping of the sentence elements given in Table 15.2, which is used quite mechanically, b) on the basis of the syntactic analysis of sentence z_1, expressed by the graph, c) on the basis of the syntactic analysis of the questions expressed by graphs, and finally d) by referring to Table 15.2 again. This entirely mechanical procedure has enabled us to find answers which are not only materially correct, but also have the required meaning with respect to the original questions.

Referring to what has been said in Secs. 15.2 and 15.3 about understanding, the operation of a machine using the method outlined above will appear to an outside observer as though the machine understood the relevant analogy. The situation appears as follows: The machine is unable to answer the four questions before the sentence z_1 and Table 15.2 are inserted in it. On insertion of sentence z_1 and Table 15.2, it changes its behaviour in such a manner as to find the correct answers to our four questions. At the same time it even answers a sentence (sentence y_1) which has not been inserted in it. The answer correctly found on the basis of analogy thus appears, according to our previous definitions, as "*understanding of analogy by machine*" (see Sec. 15.28 et seq.).

15.20 INTER-SENTENTIAL RELATIONS

We have explained in Sec. 15.10 et seq. that relations inside the sentence are expressed by so-called *syntactic pairs* whose mutual links can be illustrated by a graph. In this section we want to remind the reader in what manner the relations between individual sentences – to be more accurate, between the sentence elements of individual sentences – are expressed in the text.

The method most frequently used consists in repeating the corresponding sentence element. For instance: "*Yesterday I was at home. It was already late. Nobody was at home.*" In these three sentences, the word "*home*" is used twice. The first sentence is connected with the third one in that a particular statement relates to the same place. The designation

of this place appears therefore in the first as well as in the third sentence. Several methods have been introduced to avoid the necessity of repeating the same word time and time again. First among them is the use of pronouns and pronominal adverbs, by means of which a given word can be replaced under certain circumstances. The second method used is that of omission, which is again applied under certain assumptions to avoid repetition of a sentence element in the next sentence.

The three sentences presented above can also take the following form: "*Yesterday I was at home. It was already late. Nobody was there.*" The adverb "*there*" replaces the sentence element "*at home*". The relation between the sentences remains unchanged – only the method of its verbal expression is altered.

When investigating inter-sentential relations, we shall first pay attention especially to whether such a relation exists or not. We shall not take any account of the manner in which the relation is expressed. This enables us to become, to a considerable degree, independent of the method used to express the relation.

15.21 GRAPHS OF INTER-SENTENTIAL RELATIONS

Graphs are used again to illustrate inter-sententional relations. At the beginning we depict the entire sentence at one node of the graph. To mark the correct order of sentences in a text whose inter-sentential relations we want to demonstrate by the graph, we number the individual nodes (and, to facilitate discussion, the corresponding sentences) in the order in which they appear in the processed text.

Several relations may appear between the same sentences. We therefore illustrate equal relations by coloured connecting lines and by connecting lines drawn in some specific manner. The construction of a *graph of inter-sentential relations* will be followed by means of the following text, the graph of which is shown in Fig. 15.16. For better clarity, the text has been arranged to consist of the simplest sentences possible.

Text 1. *(The Babes in the Wood)*

1. The children left home for the forest. 2. They picked strawberries. 3. They were still small. 4. They got lost in the forest. 5. They could not

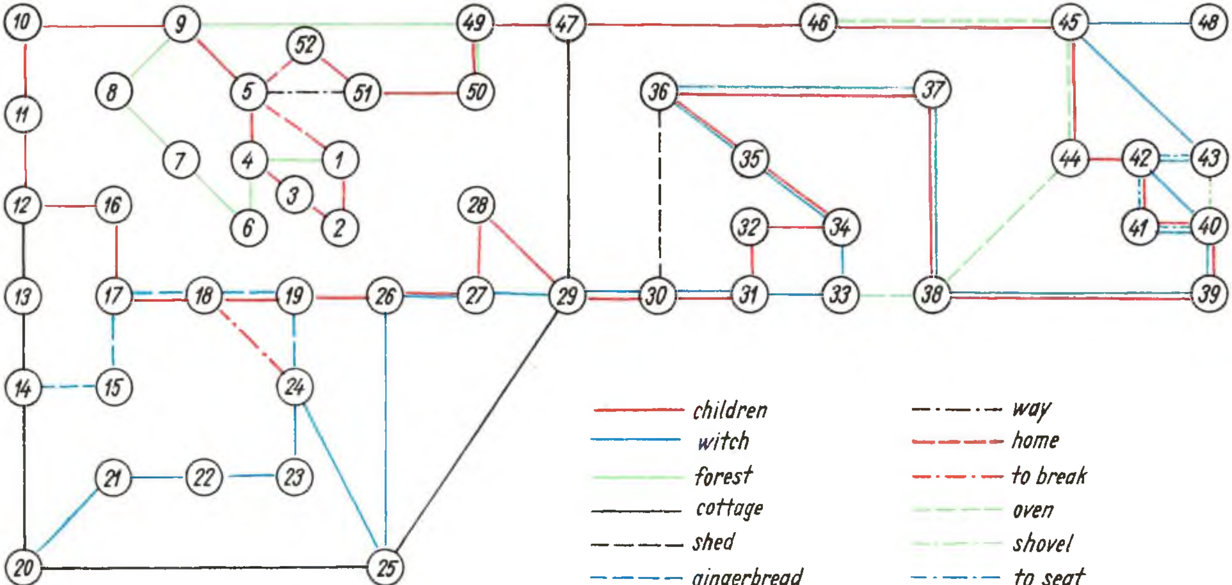

Fig. 15.16. Graph of inter-sentential relations of Text 1 (The Babes in the Wood)

find the way home. 6. The forest was deep. 7. It was wild. 8. It was old. 9. The children wandered long in the forest. 10. They were tired. 11. They were afraid. 12. In the evening they came to a cottage. 13. The cottage was small. 14. It was made entirely of gingerbread. 15. The gingerbread smelled lovely. 16. The children were hungry. 17. They wanted some gingerbread. 18. They began to break some off. 19. They ate it. 20. In the cottage there lived a witch. 21. She was old. 22. She was ugly. 23. She was wicked. 24. She heard the gingerbread breaking. 25. She came out of the cottage. 26. She saw the children. 27. The children were afraid of her. 28. They wanted to run away. 29. The witch tempted them into the cottage. 30. Then she shut them in the shed. 31. She fed them well. 32. The children fattened. 33. The witch made a fire in the oven. 34. She wanted to roast the children. 35. She wanted to eat them. 36. She let the children out of the shed. 37. She bathed them. 38. She wanted to throw them into the oven. 39. She told the children she would rock them. 40. She wanted to seat them on the shovel. 41. The children pretended they could not do it. 42. The witch showed them how to do it. 43. She sat on the shovel. 44. The children opened the oven. 45. They threw in the witch. 46. They shut the oven. 47. Then they ran away from the cottage. 48. The witch was roasted. 49. The children ran through the forest. 50. They soon came out of the forest. 51. Then they easily found their way. 52. They safely reached home.

The graph of this text, as shown in Fig. 15.16, is constructed as follows: If, in a sentence, a word occurs which is repeated in some other sentence, the numbers corresponding to the sentences involved are interconnected. To keep the graph clear and to follow simultaneously the course of the narration, the sentence containing the newly repeated word is linked to the number of the last sentence in which the word occurred. At the same time, this rule facilitates the construction of the graph. It is quite sufficient to read the text as written and to keep in mind only whether the corresponding words already occurred in the foregoing parts of the text. When, in reading the text, we find a word which already occurred in it, we seek out the place where this word was used last. We then draw a connecting line to the node containing the number of this sentence. Thus, if we proceed along any uniformly coloured line of the graph, we find on it the sentences arranged in the order as used in the text, i.e. from the lowest to the highest number. For instance, on the

green line expressing the word "*forest*" we find the numbers 1, 4, 6, 7, 8, 9, 49, 50, which means that the word "*forest*" occurs in these sentences of the text, in the given order.

A connecting line is also drawn between the sentences when the corresponding word has been replaced in the next sentence by a pronoun, or when this word has been used in a different grammatical form. For instance, in sentence 9 we find the word "*children*". This word had last been used in sentence 5 in the form of the pronoun "*they*". It occurs next in sentence 10, again as the pronoun "*they*". We see that the red line in the graph, expressing the word "*children*", leads through the nodes 5, 9, 10, etc. in succession. Thus, these sentences are related by the word "*children*".

Now let us turn our attention to sentence 12. Here the words "*children*" and "*cottage*" are brought into connection for the first time. This is revealed in the graph by the simultaneous occurrence of connecting lines of two different colours, red and black. The fact that these two words are brought into relation for the first time is shown by the corresponding node being the first in the order of enumeration where these two colours meet. Similarly, the black and the dashed blue line meet for the first time in node 14, the red and the dashed blue line in node 17.

Between the nodes 18 and 24 we find a connecting line which indicates the relation between these sentences by the words "*break off*" and "*breaking*". When recording the connections in the graph it is inessential that the words in the two sentences are not in the same grammatical form. The main thing is that they express the same action, the same subject, the same property, etc.

Similarly, in the sentences 41 and 42 we find the word "*it*" which relates to the action expressed in the preceding sentence, 40. In the graph we therefore find a connecting line between the sentences 40, 41 and 42, which shows this relation, no matter how expressed verbally. A detailed explanation of this situation will be found in Sec. 15.24 and in Fig. 15.18.

We would like to point out again, that there has been no need to pay any attention to the meaning of the words or of the looked-for relations when constructing the graph of inter-sentential connections. All the rules employed in the construction of the graph are based purely on the formal

aspect of language. For instance, we linked up sentences in which the same word occurred, without regard to its grammatical form. At other times we connected sentences containing the same word, no matter whether it was used in its verbal form or in some other form. Finally, we linked up sentences in which the given word was replaced by a pronoun. The element to which the pronoun relates again follows from the formal position of the words in the corresponding sentences. This leads to an important conclusion:

*The graph of inter-sentential relations is constructed on the basis of formally applied grammatical rules. No attention need be paid in its construction to the meaning of the words used.**)

To avoid errors we think it essential to warn the reader that the graph of inter-sentential relations expresses only relations which follow from the grammatical rules applied with respect to the text. It is therefore impossible to look in the graph for relations known, for instance, by experience, or on the basis of other knowledge not expressed by grammatical rules. Such relations include, for instance, the use of synonyms (provided they are not included in a table, etc., used in connection with the given text), the use of superior concepts, etc.

15.22 The Use of Graphs of Inter-sentential Relations in the Compilation of Abstracts

The compilation of abstracts consists in extracting a short statement of the facts which interest us in the given text. We must therefore always define or at least presume the point of view from which the contents of the text are of interest. For instance, these may be new facts contained in a technical paper, the plot described in a story, etc. The given point of view then serves as a guide for compiling the abstract. According to it we decide whether certain facts contained in the text are relevant or not.

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*) Editorial note:

It is presumed here that the problem — in itself very complicated — has been solved whether it is possible to ascertain merely from the formal characteristics of the text when two different tokens of the same word refer to the same object.

The graph of inter-sentential relations enables the abstract of a paper to be compiled from the viewpoint of the relations between individual expressions (words) used in the text. From this viewpoint, the essential sentences are those in which expressions (words) concur such as are used in some further sentence of the text together with other such words.

As can be gathered from Fig. 15.16, in text 1 the sentences 1, 4, 5, 12, 14, 17, 18, 20, 24, 25, 26, 29, 30, 33, 36, 38, 40, 41, 42, 44, 45, 47, 49, 50, 51 and 52 are those which are of importance from the viewpoint of inter-sentential relations. Let us proclaim these sentences to be the carriers of the contents of text 1. Its contents will then be as follows:

The children left home for the forest. They got lost in the forest. They could not find the way home. In the evening they came to a cottage. It was made entirely of gingerbread. The children wanted some gingerbread. They began to break some off. In the cottage there lived a witch. She heard the gingerbread breaking. She came out of the cottage. She saw the children. The witch tempted them into the cottage. Then she shut them in the shed. The witch made a fire in the oven. She let the children out of the shed. She wanted to throw them into the oven. She wanted to seat them on the shovel. The children pretended they could not do it. The witch showed them how to do it. The children opened the oven. They threw in the witch. Then they ran away from the cottage. They ran through the forest. Then they easily found their way. They safely reached home.

The graph of inter-sentential relations enabled us to omit 26 sentences as being inessential with respect to the relations between the concepts used. In deleting these sentences it was essential that the decision, which sentences to omit and which to retain as relevant to the contents, did not require us to consider the meaning of the individual sentences. This decision depended only on the rule concerning the connecting lines in the graph. This method can therefore be used for compiling abstracts of texts by machine. The machine, which cannot understand the meaning of the words, is guided by a rule independent of the word content and relating to the graph of inter-sentential relations.

In the preceding section we showed that there was no need to know the meaning of the words when constructing the graph of inter-sentential relations, but that formal grammatical rules were sufficient for this pur-

pose. In the present section we find that the utilization of this graph for compiling the abstract of a text from the viewpoint of inter-sententional relations is again independent of the meaning of the words and that we can proceed again with the aid of rules based only on the properties of the graph. These are rules which can again be applied quite formally by a machine.

15.23 The Use of the Graph of Inter-sentential Relations for Stylistic Modifications

If we submit Fig. 15.16 to a careful scrutiny, we will observe that the graph simultaneously represents the successive evocation of images bound up with the individual concepts used. Let us, for instance, consider sentence 17. In this sentence, the words "*children*" and "*gingerbread*" are found to concur. To get a correct idea of their relation given by the sentence, we must first know something about the children and something about the gingerbread. We learn about the children from sentence 16, about the gingerbread from sentence 15. However, sentence 15 does not tell us anything about how the gingerbread is related to something else. This has been done in sentence 14, which brings the gingerbread into connection with the cottage.

The narration of the text is thus regarded as the successive construction of the graph. When we start our narration, we are concerned with a text known to us, but unknown to the person for whom the narration is intended. To make the narration clearly understandable, the graph must be constructed according to certain rules. For instance, when we want to pronounce sentence 17 (construct node 17) we must first – for the sake of simplicity considering only its immediate vicinity – prepare the sentences 12 and 16 and one of the paths leading to sentence 17, and then the sentences 12, 13, 14 and 15 as the second path leading to it.

If we are concerned with the construction of the graph only, it will be seen that it is possible to use first the sentences 12, 13, 14, 15 and then sentence 16, or that we may change the order of the sentences by first pronouncing the sentences 12 and 16 and then the sentences 13, 14, 15. Only then are we ready to pronounce sentence 17. Verifying both

possibilities by applying our knowledge of the meaning of the sentences, we find that both ways are admissible from the viewpoint of a clear narration. We thus obtain:

1. *12. In the evening they came to a cottage. 13. The cottage was small. 14. It was made entirely of gingerbread. 15. The gingerbread smelled lovely. 16. The children were hungry. 17. They wanted some gingerbread.*

2. *12. In the evening they came to a cottage. 16. They were hungry. 13. The cottage was small. 14. It was made entirely of gingerbread. 15. The gingerbread smelled lovely. 17. The children wanted some gingerbread.*

In the second case we found by means of the graph, without considering the meaning of the sentences, that sentence 16 can be placed differently from the original text without detriment to the logic of the text.

From the viewpoint of a narration which would impose the least possible strain on the listener, it is suitable to keep as long as possible to a single idea (in our case a single expression, word, or notion) and to change over to another expression only when this becomes necessary in order to prepare the situation for expressing a further relation. This is what the correct styling of a given text sometimes consists in. Reverting again to the language of the graph, we say that the style of narration appears as the method by which we pass through the graph. The following set of rules provides an example for an algorithm whose application leads to a styling optimal from the particular viewpoint mentioned in the first sentence of this paragraph:

1. We pass through the graph so as to change the colour of the path followed as rarely as possible.

2. When encountering a node from which connecting lines emerge having a colour different from that over which we approached the node, we interrupt our passage in front of this node.

3. We find the node carrying the lowest number in that part of the graph from which this connecting line comes, without regard to the colour of the connecting lines.

4. We then proceed from this node, again observing rule 1.

5. When encountering several possibilities of continuation, and if there are no reasons to the opposite, we may select any of them.

Proceeding according to these rules, the best style for text 1 between the sentences 12 and 26 would be this: 12, 16, 13, 14, 20, 15, 17, 18, 19, 21, 22, 23, 24, 25 and 26. The text would then read as follows (cf. text 1):

12. In the evening they (the children) came to a cottage. 16. They were hungry. 13. The cottage was small. 14. It was made entirely of gingerbread. 20. In the cottage there lived a witch. 15. The gingerbread smelled lovely. 17. The children wanted some gingerbread. 18. They began to break some off. 19. They ate it. 21. The witch was old. 22. She was ugly. 23. She was wicked. 24. She heard the gingerbread breaking. 25. She came out of the cottage. 26. She saw the children.

The rules of optimum styling presented above are not the only ones possible. By means of various sets of such rules it is possible to arrive at different styles of narration from the viewpoint of the sequence of sentences. In "restyling" the text as described, we relied to a considerable measure on the original text. Styling a narration without using any original text as the basis would imply an attempt to construct a graph, for instance, according to our idea of the fairy tale "The Babes in the Wood", not yet put into words and sentences. To go back as far as this in the question of style exceeds the scope of this chapter. The elaboration of the problems involved belongs to the field of investigation of the higher nervous activity of man in the framework of psychology rather than into that of cybernetics.

The important thing is that, again, the rules of styling are not based on the meaning of the sentences but follow formally from the use of the graph. They are therefore applicable to the modification of style by machines.

15.24 The Graph of a Text as a Graph Made Up of the Graph of Syntactic Links and the Graph of Inter-sentential Relations

In compiling the abstract of a text in Sec. 15.22, we used only the graph of inter-sentential relations as a basis. The use of this graph enables us to eliminate some complete sentences as irrelevant to the contents. Further insubstantial relations, which may be left out

when compiling the abstract, can be found by adding to the graph of inter-sentential relations the graph of the syntactic links of individual sentences, the resulting graph being called the graph of the corresponding text. It is defined as follows:

The graph of a text is a graph of inter-sentential relations of this text, whose nodes are made up of the graphs of syntactic links of the corresponding sentences.

The coloured connecting lines between the sentences are replaced here by connecting lines of the same colour drawn, however, between the appropriate sentence elements of the corresponding sentences.

Fig. 15.17 shows part of the graph of text 1. The numbering of the nodes – now the numbering of the syntactic links – appears at the left.

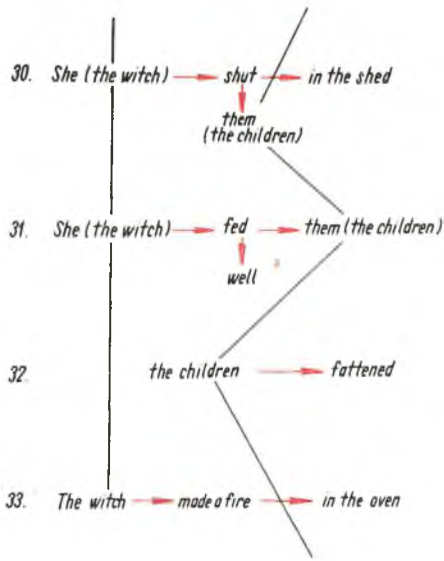


Fig.15.17. Part of the graph of inter-sentential relations of Text 1, with the individual sentences written out. The links of the inter-sentential relations are printed in black, the connecting lines of the syntactic links within the sentences are shown in red. In this context, the elements "well" and "fattened" appear as inessential. The numbers at the left indicate the corresponding sentences in agreement with Fig.15.16

The connecting lines in these graphs are printed in red. The black lines indicate inter-sentential links. Since, in this case, the inter-sentential links are unambiguous, they have not been distinguished by different colours.

Evaluating this graph from the viewpoint of the relations shown, we find that the sentence element "well" in sentence 31 is not included in any inter-sentential relation. This element may therefore be proclaimed

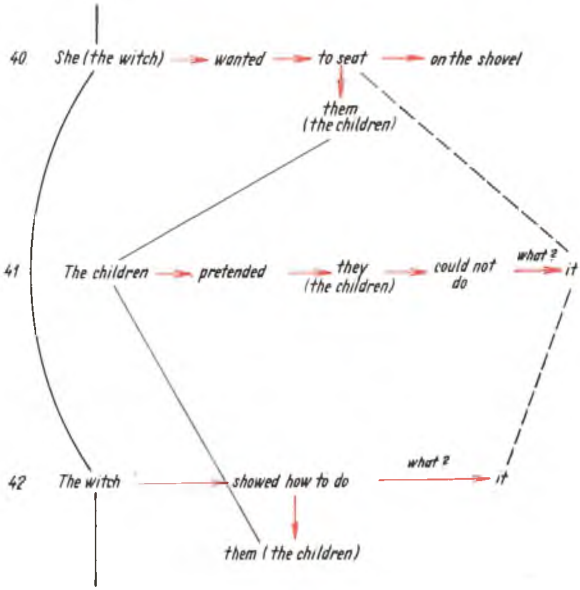


Fig.15.18. Part of the graph of inter-sentential relations of Text 1 (Fig.15.16) showing the link expressed by the pronoun "it"

to be inessential from the viewpoint of inter-sentential relations. Since the sentences used as examples are simple, this element is represented here by a single node in the graph of syntactic links. In more complicated sentences this might be a whole branch. Branches containing only nodes which have no inter-sentential relations are called inessential. By eliminating inessential branches when compiling abstracts of texts, we achieve a further simplification which does not impair the meaning of the abstract obtained.

Let us more closely investigate the graph of Fig. 15.17 from the viewpoint of inessential branches. If we omit the inessential branches in sentence 32 (represented here by the single sentence element "*fattened*"), only a single word remains. Since this word does not constitute any sentence, it cannot exist by itself in the abstract. Therefore, when eliminating inessential branches of the graph, we thereby eliminate practically the whole sentence. This new aspect permits us to formulate the abstract of a text as follows:

From the viewpoint of conceptual relations, the abstract of a text is represented by a graph of the text from which all inessential branches have been omitted.

Now let us more closely examine the inter-sentential relations whose elucidation we promised in Sec. 15.21. Fig. 15.18 shows another part of the graph of text 1, containing the sentences 40, 41 and 42. Here the pronoun "*it*" stands for the entire branch of sentence 40 which starts with the element "*to seat*". The pronoun "*it*" is therefore connected with the element "*to seat*" by a dashed line. The correctness of the connection set up is verified by replacing the pronoun "*it*" by the corresponding branch. The sentence 41 then becomes:

1. In the literal wording: *The children pretended that the children could not – (what?) – seat the children on the shovel.*

2. Retaining the original meaning, but in a more customary style: *The children pretended that they could not – (what?) – seat themselves on the shovel.*

Similarly, when we replace "*it*" in sentence 42 by the corresponding branch from sentence 40 (where the dashed connecting line is leading to), the sentence acquires the following form:

1. Literal wording: *The witch showed the children – (what?) – how to seat the children on the shovel.*

2. In a modified wording, retaining the meaning: *The witch showed the children – (what?) – how to seat themselves on the shovel.*

15.25 The Semantic Character of the Graph of a Text

Let us suppose that we have the graph of text 1 in front of us and that the word "*gingerbread*" is illegible. To be able to speak of it

without all the time evoking the image of gingerbread in our mind, let us replace it by an artificially created word, for instance "*lape*". Now let us examine the question of what can be learned from text 1 about this "*lape*" by a person who does not know the meaning-content of this word and who creates this content for himself on the basis of the text. The careful reader is certain to have noticed that at this instant it begins to be slightly unclear, whether to speak of the "meaning-content" of the word *lape*, or whether to use the "image" corresponding to the word *lape*. Sometimes we express both these possibilities by saying that we do not know what the word *lape* "means". For the sake of simplicity we shall henceforth adhere to one of these possibilities only and speak of the meaning-content of the word.

The meaning-content of the word *lape* can be derived from the given text only on the basis of relations to other words in the text, no matter whether these relations are inter-sentential or syntactic. From the graph of Fig. 15.16 we gather that "*lape*" (the blue dashed connecting line) is mentioned in the sentences 14, 15, 17, 18, 19, and 24. From these we learn that

(Sentence 14) *The cottage was made entirely of lape.*

(Sentence 15) *The lape smelled lovely.*

(Sentence 17) *The children wanted some lape.*

(Sentence 18) *The children began to break off some lape.*

(Sentence 19) *The children ate the lape.*

(Sentence 24) *The witch heard the lape breaking.*

These six sentences present the relations between *lape* and the other words of the text. These relations express the meaning-content or semantic aspect of the word *lape*. They form the meaning-content of this word as represented by text 1.

If we continue to work on the assumption that text 1 is the only basis we have, we cannot imagine under the meaning-content of the word *lape* anything but the relations of the six sentences quoted. This example already clearly shows that the meaning-content of a word changes according to the relations ascribed to it. If anybody proclaimed that *lape* was, for instance, brown, soft, etc., he would thereby define the meaning-content of this word more accurately, i.e. intensify its semantic content.

Fig. 15.19 shows the graphs of the six sentences quoted above. These sentences define by their syntactic construction the relations of the word *lape* with the words *cottage*, *children*, *witch*, in a manner redrawn in Fig. 15.20 so that every word of interest occurs only once. Where several relations exist between some of the words, they are indicated by

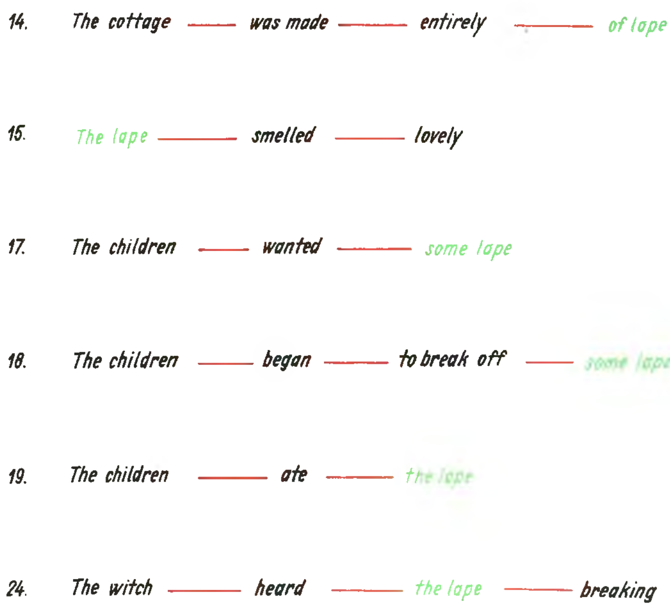


Fig. 15.19. Part of the graph of inter-sentential relations of Text 1, in which the word "gingerbread" has been replaced by the fictitious word "lape". The numbering of the sentences at the left corresponds to the numbering in Fig. 15.16

figures which correspond to the number of these relations. From this graph we gather that the text gives one relation between the word *lape* and the word *cottage*, one relation between the word *lape* and the word *witch*, and three relations between the word *lape* and the word *children*.

As we have just said, the text gives a certain number of relations. This must be stressed very emphatically. For instance, the same sentence might appear in the text (in a simple case) twice. Let this be, for instance, the sentence 14. By a formal analysis of the relations – as we perform

it here without regard to their contents — we may happen to find that the text gives two relations between *cottage* and *lape*, and not one as found before. We must again emphasize that the graph arises on the basis of a formal treatment of the text and that the number of connecting lines between the nodes of such a graph shows how many relations the text actually presents, and thus that it does not say anything about the connecting lines being equal, or different, or equal from some particular point of view, etc. This must be kept in mind when considering

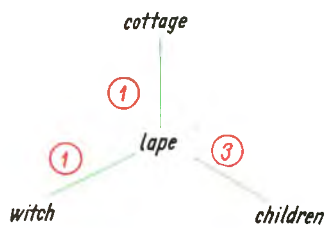


Fig. 15.20. Graphic illustration of the relations with the fictitious word "lape" presented by Text 1

the use of such a graph for further purposes. Repeating once more what has been said at the beginning, the graph of Fig. 15.20 as well as any other graph constructed in the same manner expresses how many relations and between which words the corresponding text presents by its syntactic or inter-sentential structure.

15.26 The Semantic Graph of a Text

The problem of the relation between a given word and the rest of the text is no simple matter, and we cannot content ourselves with the statement that, for instance, six connections exist between the word *lape* and the text. The relations of other words, directly connected with *lape*, to the remainder of the text will be certainly also of importance, i.e. we shall also be interested in the mutual relations between other words of the text. We shall trace these relations according to rules defined as follows:

a) We shall consider only those words which occur in the text more than once.

b) We shall examine only whether some relation between such words

is expressed in the same sentence, i.e. whether both words involved occur in the same sentence and, moreover, in the same branch (if the two words are in different branches, we do not consider them as words whose mutual relation is defined by the sentence).

c) We shall investigate in how many different manners this relation is established.

A list of the relations in text 1, defined in this manner, is given in Table 15.3. The words which are represented in Fig. 15.16 by differently coloured connecting lines are given at the top and left-hand side of the table. The number of relations, i.e. the number of the nodes in which the corresponding colours meet, will be found at the intersection of the corresponding column and row. For instance, the words *witch* and *children* will be found to meet in the same sentence fourteen times, whereas the words *way* and *home* only once. Our "unknown" word *lape* concurs three times with the word *children*, twice with the word *break* and once with each of the words *cottage* and *witch*.

Table 15.3.

The number of inter-sentential relations in text 1, as given by the graph of inter-sentential relations in Fig. 15.16.

	children	*witch*	*forest*	*cottage*	*shed*	*way*	*home*	*to break*	*oven*	*shovel*	*gingerbread*	*to seat*
children	—	15	5	3	2	2	3	1	4	1	3	3
witch	15	—	0	3	2	0	0	1	3	2	1	3
forest	5	0	—	0	0	0	1	0	0	0	0	0
cottage	3	3	0	—	0	0	0	0	0	0	1	0
shed	2	2	0	0	—	0	0	0	0	0	0	0
way	2	0	0	0	0	—	1	0	0	0	0	0
home	3	0	1	0	0	1	—	0	0	0	0	0
to break	1	1	0	0	0	0	0	—	0	0	2	0
oven	4	3	0	0	0	0	0	0	—	0	0	0
shovel	1	2	0	0	0	0	0	0	0	—	0	2
gingerbread	3	1	0	1	0	0	0	2	0	0	—	0
to seat	3	3	0	0	0	0	0	0	0	2	0	—

Fig. 15.21 represents Table 15.3 transformed into a graph, called the *semantic graph of the text*. The connecting lines of this graph express, in a similar manner to the table, which words of the text are interconnected by syntactic links. The figures marking the connecting lines indicate the number of links between the words concerned. The figures in the circles indicate the number of the corresponding word as given in the table.

The graph of the semantic links of a text can very well serve as the starting point for a quantitative evaluation of the word contents with

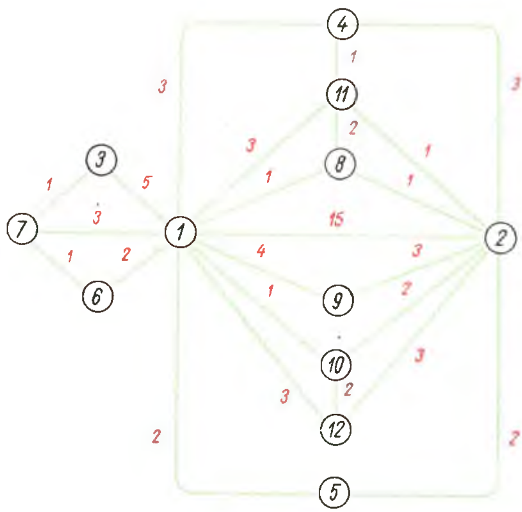


Fig. 15.21. Semantic graph of Text 1. The connecting lines between the nodes show that a syntactic relation (or, in general, a relation determined by another formal rule) exists in the text between the corresponding words. The figures marking the connecting lines indicate the number of such relations existing in the text

respect to the given text. This quantitative evaluation may be based on the number of connecting lines emerging from the corresponding nodes of the graph. This number is the measure by which the node concerned enriches the structure of the text.

Another quantitative evaluation is based on the sum of the numbers marking all the connecting lines meeting in the particular node. If we call the number marking the connecting line the weight of the corre-

sponding link, then the sum of the weights gives the total weight of the node in the text.

Table 15.4 lists the individual words of text 1 presented as nodes in the graph of Fig. 15.21. Column b) gives the number of connections

Table 15.4.

Evaluation of the semantic situation of the words in text 1.

	a	*b*	*c*
children	1	11	42
witch	2	8	31
forest	3	2	6
cottage	4	3	7
shed	5	2	4
way	6	2	3
home	7	3	5
to break	8	3	4
oven	9	2	7
shovel	10	3	5
gingerbread	11	4	7
to seat	12	3	8

a) Words of text 1; numbering in accordance with Fig. 15,21.
b) Number of relations between different words.
c) Number of all relations giving the total weight of the nodes in the text.

with other nodes, expressing the measure of enrichment of the semantic structure. Column c) gives the sum of the weights as the total weight of the node in the graph of semantic structure.

15.27 Supplementary Sentences

A new sentence supplementing the given text can exert different effects on its semantic graph:

1. The semantic graph remains unchanged.

Example 1: "*Ants live in ant-hills*". This sentence has no connection with text 1, there being no word in common. In the graph of inter-sentential relations it would appear as an isolated node.

Example 2: "*Gingerbread is crisp and brown*". This sentence has one word in common with text 1, namely gingerbread. In the graph of inter-sentential relations it appears as a node linked by a single colour, but nothing is changed in the semantic graph.

2. The sentence increases the weight of some link in the semantic graph.

Example 3: "*The witch then put some wood into the oven*". This sentence introduces a new relation between two words already occurring in text 1. These are the words "*witch*" and "*oven*". In the semantic graph this reveals itself by a change in the weight of the connecting line between the nodes "*witch*" and "*oven*" (from weight 3 to weight 4 in Fig. 15.21).

3. A new link is set up between nodes.

Example 4: "*The cottage was in the forest*". This sentence introduces a new connecting line between the nodes "*cottage*" and "*forest*" in the graph of Fig. 15.21. Thus it enriches the structure of the semantic graph.

Observing the effect of the individual instances quoted above on Table 15,4, we find that

examples 1 and 2 have no effect on Table 15.4 (or on Table 15.3 either),

example 3 increases the total weight of the nodes in text 1, i.e. in column c) of Table 15.4 the weight of the node "*witch*" is raised to 30, that of the node "*oven*" to 8 (in Table 15.3 it leads to a change in the number at the intersection *witch-oven*),

example 4 increases the number of relations between different words, so that the number in column b) corresponding to the node "*cottage*" is raised to 4, and that corresponding to the node "*forest*" is raised to 3. The number of the sum of relations of these nodes, given in column c), is raised by unity. (In Table 15.3, the zero at the corresponding intersection is replaced by a non-zero value).

15.28 GRAMMATICAL TRANSFORMATIONS

If we use certain grammatical rules in the construction of the text, we often find that the same relation can be expressed in several different ways. This also effects the syntactic construction of sentences

in different manners. There exist some language rules (which we shall call, for our purposes, transformation rules) which can be used to change the syntactic structure of sentences without affecting their meaning.

When investigating the syntactic similarities between sentences it is not enough to discover that they are not identical in the form in which they are written. We must also see whether the application of transformation rules does not lead to syntactic identity. However, this method has not yet been sufficiently elaborated to permit its application in machines.

As an example let us quote the very simple example, when we may say either "*water level*", or "*level of water*" without thereby changing the meaning of this pair. Similarly, we may say "*a man with a hat on his head*" or "*a man who has a hat on his head*". The transformation has been performed in both cases by means of simple grammatical rules. It may happen, however, that we express something in several sentences that, at some other time, we put into different sentences, the meaning remaining the same.

Let us also remind the reader that we frequently use synonyms, which make it still more difficult for a machine to deal with this situation. In such cases simple rules no longer lead to a solution. Moreover, some of these rules have not yet even been described in the literature from this point of view. As a result, it has so far not been possible to elaborate in full the problem when two texts expressed in different ways present the same relations even though they differ at first sight in their syntax and in inter-sentential connections.

Owing to the complexity of the whole problem we cannot state unequivocally of two different texts whether they present the same relations, nor does it seem likely that we shall ever be able to do so. The difficulties are still greater when the two texts are expressed by different grammars (for instance, in a different language). This is why there is not much sense in looking for absolutely equal relations in texts – the solution must be sought elsewhere. For instance, we can look at the matter as follows: We shall be able to pronounce two texts as being identical from the chosen viewpoint only in so far as the transformation rules used to compare the two texts are correct and complete. This attitude permits us better to understand that two texts may appear as very similar to one

person, while another person proclaims them to be very much different. Using our terminology, this can be explained by each of the observers having used different transformation rules for comparing the texts.

15.29 EXPLANATION BY ANALOGY

In this section we shall devote our attention to the question. whether it is possible to explain something to a machine by means of an analogy in such a manner, that the machine will be able to give direct answers on the basis of the "*instruction*" thus received. In Sec. 15.19 we have already shown that this can be done at the level of a single sentence. Let us again concentrate on the particular case where we are concerned with the use of analogy on the basis of syntactic structure and inter-sentential relations. A general case, which we are not going to deal with, would be the use of analogy based on all grammatical relations.

Table 15.5.
Equivalent terms in the analogy of Sec. 15.30.

water	*electricity*
level	*voltage*
pipe	*conductor*
termination	*junction*
flow	*current*

The problem has not yet been satisfactorily elaborated to such an extent. We shall therefore confine ourselves to a simpler case. A further simplification, introduced on purpose, is that we do not intend to use any transformation rules. This is because, on the one hand, we do not want to complicate our example unduly, and on the other because no rules exist anyway for more complicated cases, as already explained in Sec. 15.28.

In Sec. 15.30 we shall present a text which explains in what manner the following electrical concepts are interrelated: *electricity*, *voltage*, *current*, *conductor*, etc. The text explains this by the analogy with con-

ditions existing in hydraulics, the only concepts appearing in the explanatory text being: *water*, *water level*, *pipe*, etc. The text is divided into two parts. The first seven sentences belong to the so-called mapping in which we explain which concepts taken from hydraulics are used in

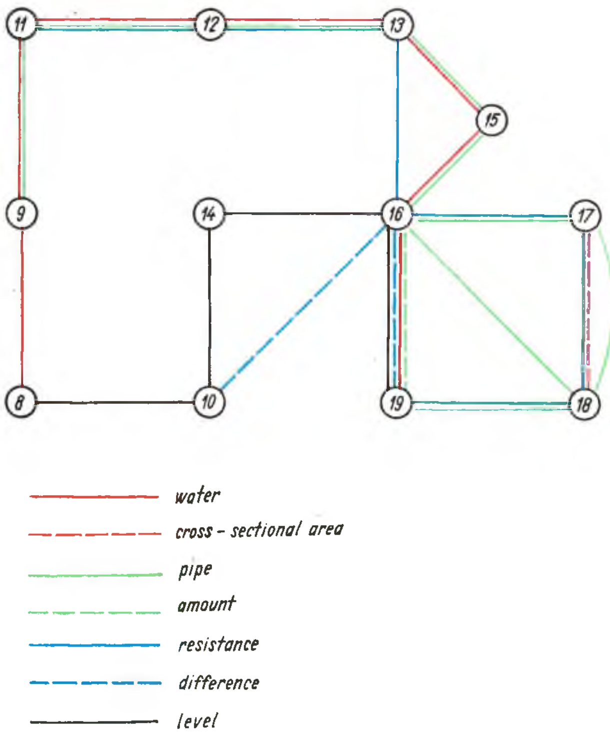


Fig. 15.22. Graph of inter-sentential relations explaining part of the text given in Sec. 15.30 and used as an example of analogy

our analogy to replace the electrical concepts (see Table 15.5). The text has been constructed so as to provide a clear example and does not claim to be complete.

The explanatory part of the text consists of the sentences 8 to 19, and describes the analogy proper. It contains a description of the behaviour of water under certain circumstances. The machine is supposed to find

the corresponding relations between the electrical concepts on the basis of this part of the text.

For the sake of completeness we should add that, when using an analogy, the text must contain the relevant mapping as well as the corresponding explanation, but there is no need to concentrate the mapping in the first part of the text as in our example. Sentences by means of which the mapping is performed are recognized in the text quite formally according to the use of verbs and expressions such as: *represents, corresponds to, is like, considered metaphorically, etc.* (The wealth of such expressions depends on the size of the vocabulary at the disposal of the machine and on the explanation of these words available to the machine. It is quite natural that, when using an expression which the machine does not "know", we cannot hope that it will be able to ascertain, for example, whether it is concerned with a sentence expressing a mapping. In such a case it is of course no better off than a human being in the same situation.)

Fig. 15.22 shows the graph of inter-sentential relations of the text presented in Sec. 15.30.

15.30 A Text Used as Analogy

1. The electric current is like a flow of water, where electricity is represented by water. 2. The electric voltage corresponds to the water level. 3. A higher voltage is represented by a higher level; similarly, a lower voltage is represented by a lower level. 4. The width of the pipe corresponds to the electric conductivity. 5. The pipe represents the electric conductor. 6. A pipe of equal width represents a conductor of equal resistance. 7. The termination of the pipe at a particular level is considered metaphorically as the function of a conductor to a node at a given voltage. 8. Water flows from the higher level to the lower level. 9. The wider the pipe the easier can the water flow through it. 10. The difference between two levels gives the energy gradient. 11. The pipe presents a resistance to the water. 12. The wider the pipe, the lower the resistance it presents to the water. 13. The narrower the pipe the greater the resistance it presents to the water. 14. In practice, the level is always measured relative to some reference level.

15. If several pipes are connected to a single node, the sum of all flows in this node is equal to zero. 16. The amount of water flowing through a pipe is directly proportional to the difference between the levels at which the pipe terminates and inversely proportional to the resistance of the pipe. 17. The resistance of the pipe is directly proportional to its length and inversely proportional to its cross-sectional area. 18. The quality of the pipe is expressed by its specific resistance, that is the resistance of a pipe of unit length and unit cross-sectional area. 19. The resistance of a pipe is found by dividing the difference in level at its ends by the amount of water flowing through it per unit time.

15.31 The Use of Analogy and its Assimilation by a Machine

A machine operates on the basis of an analogy in a manner similar to a human being. Man must first realize how the individual concepts are assigned to each other in the analogy. The machine does this by compiling a *table of equivalent notions* (see Table 15.5).

When a man is faced with a question from the sphere of electrical engineering, he first converts it into the language of the analogy. In this case, the machine replaces the words according to the table, preserving the syntactic construction of the question. The machine then finds the answer to the question transformed in this manner using the text concerning the water. It then converts the answer back into the language of electrical engineering.

If a human being continues for some time to work with an analogy in this manner, he will eventually stop converting questions into the language of the analogy, and will transfer the corresponding relations directly into the language of electrical engineering.

A machine can be arranged to operate in a similar manner. This will be useful in case it needs the relevant relations more frequently. In the machine, conversion into the language of electrical engineering means that the machine replaces the notions listed in the table so that the text will consist of electrical engineering concepts in place of the corresponding terms used in hydraulics. It will then be able to answer questions from the sphere of electrical engineering directly on the basis of the new

text, without always having to revert to the input and output mapping, i.e. the translation from one language into the other. The creation of this new text is then called the *assimilation of the particular analogy*.

Assimilation of the analogy thus appears as the replacement of the relations presented in the analogy by the determination of the direct relations.

When a human being assimilates a particular analogy in this manner, we shall not be able to conclude this immediately from his behaviour. His answers will be the same, no matter whether he uses the analogy or the assimilated relations. Assimilation is important only because it permits the relevant answers to be found faster and simpler. Similarly, assimilation is not necessary for the machine. In spite of this we speak of this assimilation to recall once more that this possibility also exists in the machine and that, therefore, the use of language by a machine may, in this respect, possess a similar character and find similar application as in man.

15.32 Restrictions on the Use of Language by Machines

Already when reading Sec. 15.28, the reader is certain to have felt that the use of language based on the knowledge of grammar alone, no matter how thorough and how highly developed the rules are, does not lead in machines to an exploitation as full as that applied by man. This is because, on the basis of the knowledge and the connections defined by grammar, it is possible to ascertain, use, and operate only such relations which can be expressed grammatically. This conclusion, which at first sight appears as self-evident, immediately forces a new question upon us: What are these further relations which, although they are not defined by grammatical rules, we utilize in language?

Let us remember what a human being does with the words he takes up. He does not store them in his memory in the form in which he receives them, but according to their meaning he converts them into acoustic, visual, gustatory and other images. When be operates in his imagination with what he received in the form of words, he works not only with them but very frequently with images evoked in him by these

words. When he seeks the solution of a given problem or the answer to some question, he very rarely does so on the basis of grammatical transformations alone, since these would be too meagre in the majority of cases. He combines the images evoked by words in accordance with other than grammatical rules. For instance, when solving a geometrical problem, he imagines triangles, circles, angles, straight lines, which he even puts to paper if necessary, pores over them, etc. Even though he may express his cogitations in words, he does not seek the solution on the basis of grammatical rules (which only govern the description of what his imagination produces), but goes by geometrical rules which surely have not much in common with grammatical rules. Similarly, when listening to music, contemplating some new design, thinking of the shortest way to the theatre, etc., he does not rely on grammatical connections but bases his considerations on relations known by experience, on physical laws, geometrical rules, mathematics, logic, etc. He then uses language chiefly to describe the progress of his thoughts or to inform his environment of the result of his work.

So far we have not considered the possibility of language taking part in the transformation of images. Actually, the transformation of images, i.e. the function of our imagination, is based to a considerable extent on the knowledge of language.

When speaking of a machine operating on the basis of language, we have confined ourselves all the time to a method based on grammatical relations. As long as machines will be unable to form visual, acoustic and other images and operate upon them in their imagination, they will be unable to overcome this restriction.

Papers which have lately appeared in scientific literature show that it is possible to deal quite seriously with the problem of "recasting images", i.e. converting acoustic percepts and images into visual images, visual images and percepts back into acoustic images, etc. As soon as machines start working by the aid of such "operations", we shall have created conditions which will enable us to speak, in connection with machines, in a far wider sense than heretofore of what we call, in man, the second signalling system (see Chapter 16).

CHAPTER 16

SENSORS IN THE SERVICE OF INANIMATE SYSTEMS

16.1 INTRODUCTION

Influenced by cybernetics, we have lately learnt to regard the input and output devices of data-processing systems – their peripheral equipment – as sensors and effectors with the task of mediating the contact between the machine and its environment. However, it was not until the time-sharing principle was introduced, that the application of machine sensors was raised to a higher level. As a result of the introduction of this principle it proved necessary to seek advice in already existing complicated systems – living beings – on how best to fit the working of such a sensor to the operation of the rest of the system, how best to divide the work between the peripheral equipment on the one hand and the computer on the other, how best to organize the operation of many concurrently operating sensors, some groups of which are, moreover, engaged in the solution of one problem, other groups in that of some other problem. It appears with increasing clearness that, according to the example of living nature, every more complicated input or output device of a machine should be regarded as a unit independent to a certain extent, capable of adapting its activity to the instructions of the machine. This is why such a unit usually incorporates, in addition to the proper device intended to pick up information, also its own control unit, memory, and other auxiliary equipment.

In accordance with the ideas propounded above, the problem of the sensors in inanimate systems falls into two main parts, namely:

1. The design of a suitable sensor and the determination of its own function.

Note: Whenever the term "image" is used in this chapter, it stands for "optical image" and must not be confused with the identical term employed in Chapter 14 to denote "mental image".

2. The determination of the principles of co-operation between the computer and this sensor (i.e. devising the fundamental algorithms and programs for the use of the sensor by the computer).

16.2 Visual Sensors

In this chapter we are going to deal with visual (optical) sensors. Out of the many possible sensors we have chosen visual sensors because we consider the problems concerned with their construction and use to be the most interesting. These problems are so extensive and many-sided that very much concerning the design and application of other sensors can be learnt from their investigation. When considering visual sensors, we are not thinking of existing devices already used in machines. We only want to discuss a number of problems related to their realization so as to make it clear that equipping any engineering system with an entirely new accessory does not simply involve only the construction of the sensor from the technical aspect. The introduction of a new supplementary device is always accompanied by problems concerning not only the use of the supplement, but also that of the entire equipment fitted with it. This is why it is also necessary to solve problems of the methods of application, of the adaptation of the other functions of the machine to the new supplement and, last not least, the approach of its designer to its application. This aspect cannot and must not be overlooked, especially when considering the new points of view introduced by cybernetics. The passages of this book concerned with visual sensors are intended to clearly illustrate just this character of cybernetic problems. While expounding these problems, however, we also want to penetrate to a sufficient depth in order to be able to solve the technical aspects of the matter as clearly as possible. For this purpose we shall have to use in some passages a symbolic notation quite common in the language of engineering and mathematics, though perhaps not quite suited to other branches. We therefore advise readers who are more interested in our approach to the solution of the problem as such than in the engineering realization, to read the passages concerned with the latter only cursorily (chiefly Secs. 16.9 to 16.13). They can do so without losing the thread of the argument.

When designing a visual sensor, we must first make clear which of its functions fall into the proper province of the sensor itself, and which of them are a matter for the superior organs of control. Such a reflection leads to the conclusion, that a visual sensor must comprise the following principal parts:

1. *A device for the perception of the image of the environment within the visual field of the sensor,*
2. *An analyser of the perceived image,*
3. *A motion device for the formal adjustment of the image perceived,*
4. *A control unit* designed to accept instructions from the machine and to control the function of the visual sensor.

The pertinent block diagram, to be described farther on, is shown in Fig. 16.1.

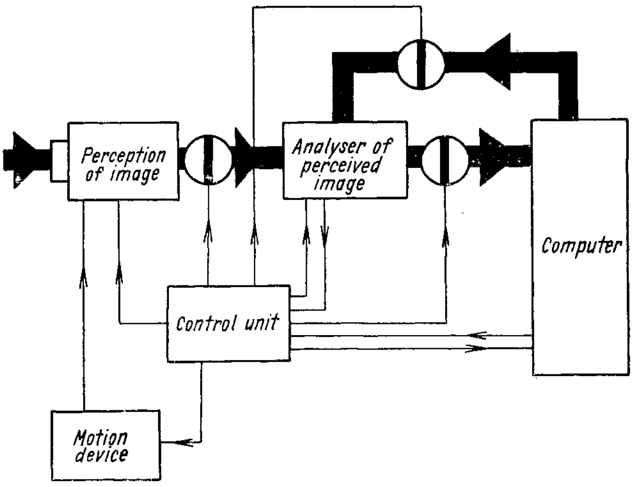


Fig. 16.1. Block diagram of visual sensor for a computer

16.3 Devices for the Perception of Images

The heavy lines in Fig. 16.1 indicate the path of the optical signals received from the environment, i.e. the information path. The light lines indicate control paths. The optical signals arriving from the

environment first enter the device for the perception of images. This device is intended to convert the optical signals into electrical signals which can be handled by the computer. This action closely resembles that of the eye in living systems. The environment, as far as it lies within the visual field of the eye, is projected by an optical system upon the retina whose task it is to convert the optical signals into signals suited to the nerve pathways, i.e. into neural impulses (see Chapter 10). In our exposition we shall assume that the device for the perception of images is represented by a television camera. The optical system of the camera projects the image of the environment upon the target of the camera tube (for instance, an image orthicon) which, for our purposes, we shall call the retina of the visual sensor.

To facilitate further explanations, we shall assume that the television camera used as our device for the perception of images operates in a high-contrast environment without half-tones. The elementary signals perceived will thus correspond to light and darkness only, and will be interpreted in the usual manner as the values 1 and 0 respectively. We shall further assume that the retina of the camera is capable of distinguishing (i.e. has a resolution of) 100 lines, with 100 dots in each line. Let this quadratic field of 10^4 bits be scanned, for instance, once per second. The set of 10^4 two-valued signals, scanned in this way within the same second in the established manner, will be called one picture and denoted by the letter A. The signals of different pictures, picked up by the same spot on the retina, will be called equi-positioned unless explicity stated otherwise.

16.4 THE ANALYSER OF THE PERCEIVED IMAGE

From the device for the perception of images, the picked-up signals proceed to the analyser of the perceived image. Its task is to analyse the picture in accordance with the instructions received from the control unit. The fundamental tasks of this analysis are:

1. Ascertaining the identity of two pictures.
2. Determination of identical or, if necessary, non-identical parts of two pictures.

3. Ascertaining the so-called boundaries in the given picture.
4. Ascertaining newly arisen boundaries.

The analyser is connected with the central part of the digital computer by a path marked in Fig. 16,1 by a wide stripe. This path serves to transfer information from the analyser to the computer. The information entering the computer over this path may consist either directly of the images intercepted by the retina, parts of these images selected by the analyser, or even of information in the form of a simple answer given by the computer to the sensor. Such an answer may, for instance, concern the question of whether the pattern transmitted by the memory of the computer to the sensor is equal to a part of the image being picked up by the sensor, etc. In the course of our explanation we shall have more opportunity to become more closely acquainted with this path. The information path leading from the computer to the analyser is used for the transmission of information in the direction from the memory of the machine to the analyser. This path will be used whenever the sensor has to pass to the computer a message saying that an expected distinct situation has arisen in the visual field. In that case the sensor must, of course, dispose of some information concerning the situation which is expected to arise. This information is supplied by the computer from its memory directly to the analyser.

The inclusion of the two information paths between analyser and computer in the block diagram is intended to emphasize that, for the best possible utilization of the sensor, facilities must be provided for obtaining new information by comparing the pattern under observation with a pattern previously stored in the memory of the computer. In this case it does not matter whether this prior pattern was picked up in the past by the sensor involved, or recorded in the memory from some other source. We must realize, of course, that there may be cases when such comparisons of patterns are left to some part of the computer proper, so that the path leading from the computer to the analyser will disappear from the block diagram of the sensor.

The inclusion of the analyser in the sensor may be discussed in the same manner. We are here faced with the question of whether to leave some particular work, which has to be done, to the programmers or whether to build the pertinent fixed routines into the machine. In our

exposition we prefer to adhere to the method shown in our block diagram, since this enables us to penetrate more closely to the core of the matter. All the same, we are aware of the fact that many of the functions which we here consider to be built in, can be left out of the automatic functions of the sensor at the usual cost of increased demands made on routine programming work.

To get a closer view of the part played by the analyser within the framework of the sensor as well as of its function, we shall now direct our attention to one of the possible requirements – the preliminary processing of information in a manner designed to facilitate the work of the computer when distinguishing various objects from the rest of the environment. A prerequisite is that the analyser have two images at its disposal, and that in each image the position of the object be slightly different with respect to the rest of the environment.

If we adhere to our initial assumptions concerning black and white scanning, the possibilities of distinguishing some object from its environment are reduced to two basic methods. The first of these involves the possibility of the mutual comparison of two pictures, with the object under observation assuming in each of them a slightly different position relative to the background. In this operation we assign the main role in the analyser of the visual sensor and to which we shall devote our main attention in this chapter. The second method consists in distinguishing the object by tracing its outlines. This type of operation, which is based on the co-operation of the analyser, the motion device of the sensor, and the program of the computer, will not be treated in greater detail.

16.5 THE MOTION DEVICE OF THE SENSOR

The device for the adjustment of the visual percept forms the third part of the block diagram in Fig. 16.1. This is an analogy to the eye muscles in living systems. The functions of this part are multitudinous. Let us list the most important ones:

a) Rotation of the optical axis of the visual sensor, so as to enable it to follow moving objects as long as possible. In principle, this function permits an artificial expansion of the visual field of the sensor.

b) Opening and closing of the iris diaphragm so as to obtain the optimum percept under varying lighting conditions.

c) Coordination of the axes of observation when using several sensors simultaneously to observe the same portion of the environment. This allows of stereoscopic perception which, as will be shown later, is of great importance in distinguishing immovable objects from the background.

d) Control of the size of the image projected onto the retina.

The construction of this part will not be dealt with in detail, since this is only a question of the application of well-known engineering principles. In some cases, however, we shall assume that the operation of this part is linked with the instructions issued by the control unit of the sensor.

16.6 THE CONTROL UNIT

The task of the control unit is to accept instructions from the computer and to link them to the corresponding function of the individual parts of the sensor.

The principal activities of the control unit can be divided into four parts. They are:

1. Control of the function of the analyser. According to Sec. 16.4 this involves, in our case, the performance of four different actions.

2. Automatic tracking of the given object in the visual field of the sensor, either with a static background and a moving object, or with a relatively static object and a moving background. In some cases both these possibilities will be involved.

3. Automatic tracking of a given object which changes its shape, for both alternatives mentioned in para. 2. This activity must be specified more accurately by data concerning the magnitude of the change in shape for which the object under observation is still to be regarded as the originaly defined object. It is also advisable to state whether the change in shape is to be measured with respect to the originally defined shape or with respect to the shape last scanned.

4. Control of the motion device of the sensor.

The four points presented above show that the functions of the control unit are highly diversified. The set of instructions intended for the visual sensor may be compared to the instruction code of the computer. There are certain instructions necessary for the function of the computer and some others which only serve to facilitate the work of the programmer so as to make the use of the machine more flexible. The determination of a suitable instruction code is a matter for co-ordinating the purpose of the machine, the flexibility of its utilization and the possibilities of realization, affected by many other factors. Similarly, the choice of instructions for controlling the function of the visual sensor will depend on numerous factors which must be separately considered from case to case. We shall therefore confine ourselves to an explanation of the basic functions and activity of the visual sensor in a machine, no matter whether these functions are induced by a single instruction or by several simpler instructions.

16.7 The Use of the Visual Sensor by a Computer

The visual sensor is regarded, in a similar manner to other sensors of the computer, as an executive organ subordinate to the computer. It is thus the central part of the computer which imposes tasks upon the sensor, formulated by means of instructions intended for the sensor. The tasks imposed upon the sensor by the computer can, in principle, be characterized as follows:

1. What kind of information concerning the visual field does the computer require (whether to ascertain the presence of an object of given shape, or to ascertain the shape of an object at a certain distance, or simply to find whether anything moves in the visual field, or to ascertain the shape of a moving object, etc.).

2. What kind of action is the sensor to deduce on the basis of changes observed in the visual field, without further interference by the computer (e.g., whether to track a moving object by turning after it, whether to track a given object even if it alters its shape, whether to transmit to the

computer a prearranged signal as soon as a certain situation arises in the visual field, etc.).

3. In what manner the information found is to be processed before being handed over to the computer (whether a picture of the whole field of vision is to be transferred to the computer, or whether to supply only the shape of an object found to have moved, while suppressing the background, or whether to hand to the computer only the outline of some object, etc.).

16.8 How to Distinguish an Object by the Comparison of Several Images

As we have already mentioned, in order to be able to distinguish an object from its environment by means of two images, the pictures of the object must occupy in each of them a different position relative to the background. Such two pictures can be obtained by some of the methods listed below:

1. The simultaneous scanning of two pictures, each from a slightly different side. This method which is well known in living nature presumes the simultaneous use of two visual sensors.

2. The scanning of two pictures at different times. This method is applicable even with a single sensor in cases where the objectm oves in the field of vision.

3. A combination of the two foregoing methods; a single sensor is used, the position of the sensor being changed in space before the second picture is scanned.

There are cases where three pictures are required to obtain the full outline of an object that is at rest with respect to the environment, the image of the object being shifted in these pictures relative to the environment in two different directions. This result can be achieved by using suitably placed sensors for the simultaneous perception of all three images, or a single sensor successively located in three different positions. Of course, the relative shift is governed by the laws of perspective which must be respected. From these rules it follows directly that an object

cannot be distinguished from that part of the environment which is at the same distance from the sensor as the object. It will be useful to remember that an interesting combination of the two aforesaid methods is encountered in living nature. For instance, man uses two eyes, thus obtaining two images in which the object under observation is shifted relative to the background in the direction of the line which connects the two eyes. When observing the horizontal outline of an object, he obviates this difficulty by moving his head up or down, or by inclining it so that the line connecting the eyes is deflected from the horizontal plane. If that is not sufficient, he tries to shift the whole head to a new position. In other cases he tries to move the head so as to obtain a suitable contrast between the observed edge and the background (e.g., a volleyball player, when playing in the dusk, always tries to keep the sky as the background for the upper edge of the net). This note, which concerns living nature, brings us back again to the necessity of leaving the examination of the full outline to the method (or algorithm) by which the visual sensor is used, which must take account of the numbers of sensors available as well as of the possibilities of controlling these sensors and their position.

16.9 The Comparison of Two Patterns

The comparison of two patterns, $\mathbf{A}_1$ and $\mathbf{A}_2$, enables us to ascertain whether they are identical or differ in some respect. This comparison is performed by means of the logical operation of non-equivalence, by applying this operation to the comparison of all equi-positioned elements of the two patterns. Let

$$a_{1,i,j} \in \mathbf{A}_1$$

and

$$a_{2,i,j} \in \mathbf{A}_2$$

be equi-positioned elements of the patterns to be compared, $\mathbf{A}_1$ and $\mathbf{A}_2$. In addition, let $d_{i,j}$ be an equi-positioned element of the resulting set $\mathbf{D}$, so that (in the notation of Boolean algebra, see Chapter 8) we have

$$a_{1,i,j} \cdot \bar{a}_{2,i,j} + \bar{a}_{1,i,j} \cdot a_{2,i,j} = d_{i,j} \tag{16.1}$$

for $i = 1, \ldots, n$, $j = 1, \ldots, n$. This leads to two solutions:

1. All elements $d_{i,j}$ of set $\mathbf{D}$ are zero. That means that the patterns $\mathbf{A}_1$ and $\mathbf{A}_2$ are identical. For practical purposes, this identity can be defined by the logical sum of all elements $d_{i,j}$ of set $\mathbf{D}$ being equal to zero. In this case, $\mathbf{D}$ is called a zero set, in symbolic notation $\mathbf{D} \equiv 0$.

2. Not all the elements $d_{i,j}$ of set $\mathbf{D}$ are zero. In this case the patterns $\mathbf{A}_1$ and $\mathbf{A}_2$ are not identical. The non-zero elements of set $\mathbf{D}$ indicate in what respect the two sets $\mathbf{A}_1$ and $\mathbf{A}_2$ differ. $\mathbf{D}$ is then called a non-zero set, in symbolic notation $\mathbf{D} \not\equiv 0$.

According to the circumstances under which the non-zero set $\mathbf{D}$ arises, various pieces of information can be derived from it. When the sets $\mathbf{A}_1$ and $\mathbf{A}_2$ are produced as two successive patterns scanned by a single sensor which did not change its position, $\mathbf{D} \not\equiv 0$ means that some change (a movement) must have occurred in the visual field. In case the sensor was charged with the task of drawing attention to movements in the visual field, then the result $\mathbf{D} \not\equiv 0$ is a signal indicating that such a movement has just taken place. Fig. 16.2 shows the block diagram for this case. The rectangle marked S indicates the place where the image is produced on the retina. Set $\mathbf{D}$ again serves as the source of information concerning the magnitude of the change in the image under observation.

When $\mathbf{A}_1$ and $\mathbf{A}_2$ are produced as images simultaneously scanned by two different sensors, $\mathbf{D} \equiv 0$ means that, within the resolving power of the sensors, there are only such objects in their field of vision, which are at approximately the same distance from the sensors and lie at the point of intersection of their observation axes. Fig. 16.3 shows a block diagram illustrating this case. Under the circumstances quoted, the signal $\mathbf{D} \equiv 0$ indicates that, for instance, the two sensors are aimed at a solitary object in the visual field, whose depth is not larger than the depth of focus of the sensors at the given distance. Conversely, the signal $\mathbf{D} \not\equiv 0$ indicates that there is at least one object in the visual field, at which the sensors are not aimed.

The derivation of set $\mathbf{D}$ from the sets $\mathbf{A}_1$ and $\mathbf{A}_2$ is written symbolically as follows:

$$\overline{\mathbf{A}}_1 \,.\, \mathbf{A}_2 + \mathbf{A}_1 \,.\, \overline{\mathbf{A}}_2 \equiv \mathbf{D}\,. \tag{16.2}$$

This operation is indicated in the illustrations by the symbol

$$\Leftarrow\!|\!\Rightarrow$$

Eq. (16.2) has the following meaning:

a) in case 1., equation for ascertaining movement in the visual field,

b) in case 2., equation for ascertaining the presence of an object in the plane onto which the sensors are focussed.

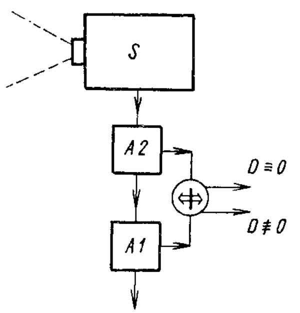


Fig. 16.2. Block diagram for ascertaining movement in the visual field of a static visual sensor. The signal **D** $\equiv 0$ *indicates rest, the signal* **D** $\not\equiv 0$ *indicates movement*

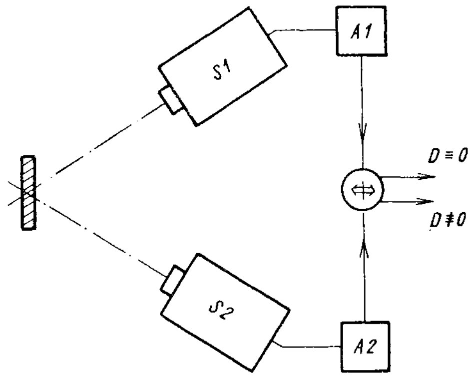


Fig. 16.3. Block diagram for ascertaining the position of objects in the visual field of sensors $\mathbf{S}_1$ *and* $\mathbf{S}_2$*. The signal* **D** $\equiv 0$ *indicates that all objects are in the plane onto which the sensors are focussed. The signal* **D** $\not\equiv 0$ *indicates that there are objects in the visual field of the sensors which are outside this plane*

16.10 Boundaries in the Perceived Picture

Fig. 16.4 shows a view of the retina of a sensor, the small circles indicating light-sensitive spots. From these spots the scanning beam derives the signal 0 or 1. The image scanned by the beam will be called the perceived picture (denoted by **A**). In our example, picture **A** is always composed of 10^4 dots. The boundary between light and darkness

in the scanned picture reveals itself in that neighbouring picture elements on one side of it are light, on its other side dark. The position of the boundaries thus belongs between two neighbouring picture elements. Since the picture elements of picture **A** are arranged in lines and columns,

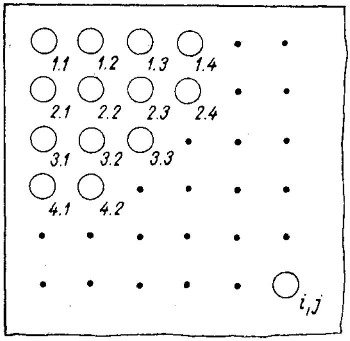


Fig. 16.4. Designation of light-sensitive spots on the retina of the sensor

we may speak of line boundaries as the places in the centre between neighbouring elements of the same line, and of column boundaries as the places in the centre between neighbouring elements of the same column. To the set of picture elements in picture **A** we thus allocate a new set, which we call the set of light boundaries, in short the set of boundaries, and denote it by the symbol **B**. The set of boundaries **B** comprises both line and column boundaries.

From the mathematical point of view, set **A** is regarded as a set of two-dimensionally distributed two-valued variables, whose number and arrangement correspond to the dots on the retina of the respective sensor and their arrangement. In our example we have selected an arrangement of dots in a square matrix with $n^2 = 100^2$ elements. Set **B** contains $n-1 = 99$ boundaries in every line, and the same number in every column, so that the total number of elements in set **B** is $2n(n-1) = 19{,}800$.

In visual perception it is of importance to have the possibility of suppressing some parts of the picture. For this purpose we shall use oper-

ations to be performed either upon various sets **A**, or upon various sets **B**.

The set of boundaries **B** is obtained from set **A** by a transformation called **R**. Expressed symbolically, we have

$$\mathbf{B} \equiv \mathbf{R}(\mathbf{A}). \tag{16.3}$$

The transformation R will be understood to mean the derivation of elements of set **B** from the elements of set **A**, so that

$$a_{i,j} \cdot \bar{a}_{i,j+1} + \bar{a}_{i,j} \cdot a_{i,j+1} \equiv b_{i,j-(j+1)} \tag{16.4}$$

$$a_{i,j} \cdot \bar{a}_{i+1,j} + \bar{a}_{i,j} \cdot a_{i+1,j} \equiv b_{i-(i+1),j}\,,$$

where the subscripts i, j indicate the position of the corresponding element in set **A**. The first equation defines the line boundaries, the subscript $i, j - (j + 1)$ indicating, that element $b_{i,j}$ is derived from line i of the matrix **A** as the boundary between the elements j and $j + 1$. Similarly,

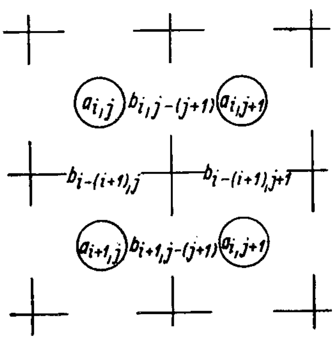


Fig. 16.5. Graphic illustration of the position of picture elements in the sets **A** *and* **B**. *Elements a represent the light-sensitive spots on the retina, elements b represent their boundaries*

the second equation defines the column boundaries, where the subscript $i - (i + 1)$ indicates that element $b_{i,j}$ is derived from column j of matrix **A** as the boundary between the elements i and $i + 1$.

The positions of the elements of sets **A** and **B** are clearly shown in Fig. 16.5.

According to the relations presented above, the elements of set **B** show whether there is a boundary in a particular place of picture **A** or not. If, in some particular place, we get $b_{i,j} = 1$, this means that there

is a boundary in this place in picture **A**. Conversely, $b_{i,j} = 0$ indicates that there is no boundary at the corresponding place in picture **A**. As will be shown later, set **B** is of importance to the determination of the shape and position of objects as well as to the discrimination between the object and its environment.

16.11 COMPARISON OF TWO SETS OF BOUNDARIES

Two sets $\mathbf{B}_1$ and $\mathbf{B}_2$ will be compared by performing the operations (16,5) on the elements of sets $\mathbf{B}_1$ and $\mathbf{B}_2$, thus obtaining the elements e of a set **E** so that

$$\bar{b}_1 \, . \, b_2 \equiv e \, , \tag{16.5}$$

where b_1, b_2 and e are equi-positioned elements of the sets $\mathbf{B}_1$, $\mathbf{B}_2$ and **E** respectively. Symbolically expressed, this operation is written in abridged form as follows:

$$\bar{\mathbf{B}}_1 \, . \, \mathbf{B}_2 \equiv \mathbf{E} \, . \tag{16.6}$$

The significance of this operation again depends on the manner in which the sets of boundaries $\mathbf{B}_1$ and $\mathbf{B}_2$ are obtained:

1. Sets $\mathbf{B}_1$ and $\mathbf{B}_2$ are derived from the sets $\mathbf{A}_1$ and $\mathbf{A}_2$ which represent two successive patterns. The value 1 then appears in set **E** only at the place where a change of boundary occurs in set $\mathbf{A}_2$. Thus, for instance, if there is some boundary in the background which remains the same on both pictures, it will not appear in set **E**. Let us assume that there is an object in the visual field which changes its position. Again, the boundary between the object and the background does not appear in set **E** because, owing to the object having moved, this boundary disappears from the picture $\mathbf{A}_1$. The new position of the object in picture $\mathbf{A}_2$, however, leads to the appearance of a new boundary in this picture. This new boundary does appear in set **E**. The operation described by Eq. (15.6) is thus used to determine new boundaries appearing in picture $\mathbf{A}_2$. These boundaries relate to an object which has moved. In this case, set **E** is called the perceived boundary of a moving object.

2. Sets $\mathbf{B}_1$ and $\mathbf{B}_2$ are derived from pictures scanned simultaneously by two different sensors. In this case, the object onto which the two sensors are aimed is shifted relative to the background. According to Eq. (16.6), those boundaries from picture $\mathbf{A}_2$ which do not occur in picture $\mathbf{A}_1$, now appear in set $\mathbf{E}$. When both sensors are focussed on the object, its boundaries appear on both pictures simultaneously. This is why these boundaries do not appear in set $\mathbf{E}$. Conversely, since the sensors are focussed on the object, the boundaries of the background of the object appear in every picture in a different position. Set $\mathbf{E}$ will then contain

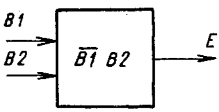


Fig. 16.6. Graphic symbol for deriving set $\mathbf{E}$ from sets $\mathbf{B}_1$ and $\mathbf{B}_2$

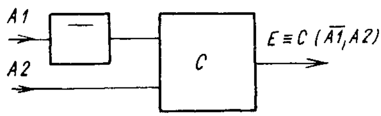


Fig. 16.7. Graphic symbol for deriving set $\mathbf{E}$ from sets $\mathbf{A}_1$ and $\mathbf{A}_2$

the boundaries of the background which appears on picture $\mathbf{A}_2$. In this case we thus suppress the percept of the object and register the background. On the other hand, if we wanted to ascertain the object, focussing on the background will cause the boundaries on pictures $\mathbf{A}_1$ and $\mathbf{A}_2$ to merge, so that they do not appear in $\mathbf{E}$. The object, however, assumes a different position in each picture, so that the boundaries of the object, which are on picture $\mathbf{A}_2$, will appear in set $\mathbf{E}$. In this case, $\mathbf{E}$ is called the set of boundaries on the background or, as the case may be, the set of boundaries on the object.

Eq. (16.6) thus expresses the fundamental operation necessary for

a) determining the outlines of an object,
b) distinguishing a moving object,
c) suppressing the percept of the rest of the environment.

Fig. 16.6 shows the graphic symbol for obtaining set $\mathbf{E}$ from sets $\mathbf{B}_1$ and $\mathbf{B}_2$.

To abbreviate our symbolic notation, it will be advantageous to introduce a new symbol, $\mathbf{C}$. This symbol will be used in a sense similar to that of the symbol of a function, $\mathbf{F}$, to express set $\mathbf{E}$ by means of the sets

$\mathbf{A}_1$ and $\mathbf{A}_2$ as follows:

$$\mathbf{E} = \mathbf{C}(\overline{\mathbf{A}}_1, \mathbf{A}_2) . \tag{16,7}$$

This symbol is then taken to mean that the set $\mathbf{E}$ was generated by our having submitted the sets $\mathbf{A}_1$ and $\mathbf{A}_2$ to the transformation R according

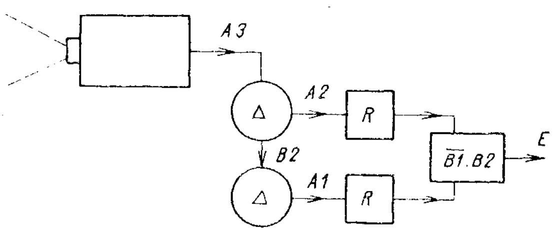


Fig. 16.8. Block diagram of circuit for obtaining set **E** *by a single sensor*

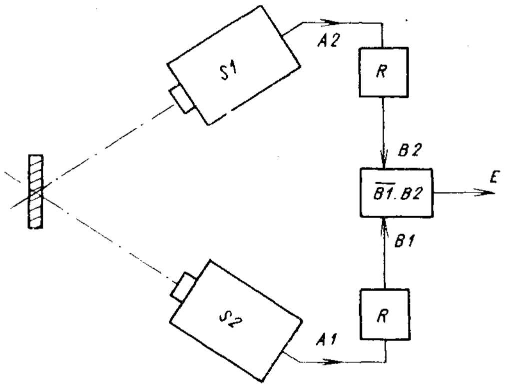


Fig. 16.9. Block diagram of circuit for obtaining set **E** *by two sensors*

to Eq. (16.1), thus obtaining the sets $\mathbf{B}_1$ and $\mathbf{B}_2$, upon which we then performed the operation (16,6). Thus,

$$\mathbf{E} \equiv \overline{\mathbf{B}}_1 \,.\, \mathbf{B}_2 \equiv (\overline{\mathbf{R} \,.\, \mathbf{A}_1}) \,.\, (\mathbf{R} \,.\, \mathbf{A}_2) \equiv \mathbf{C}(\overline{\mathbf{A}}_1, \mathbf{A}_2) . \tag{16,8}$$

Fig. 16.7 illustrates the graphic symbol for obtaining set $\mathbf{E}$ from the sets $\mathbf{A}_1$ and $\mathbf{A}_2$. Fig. 16.8 shows the block diagram of a circuit for obtaining set $\mathbf{E}$ by means of a single sensor, Fig. 16.9 that of a circuit for obtaining this set by means of two sensors.

16.12 Block Diagram of an Analyser and Means for its Realization

Fig. 16.10 shows the logic diagram of an analyser. This diagram is intended to give a fundamental idea of the technical difficulties involved in its realization. We assume that the picture is scanned

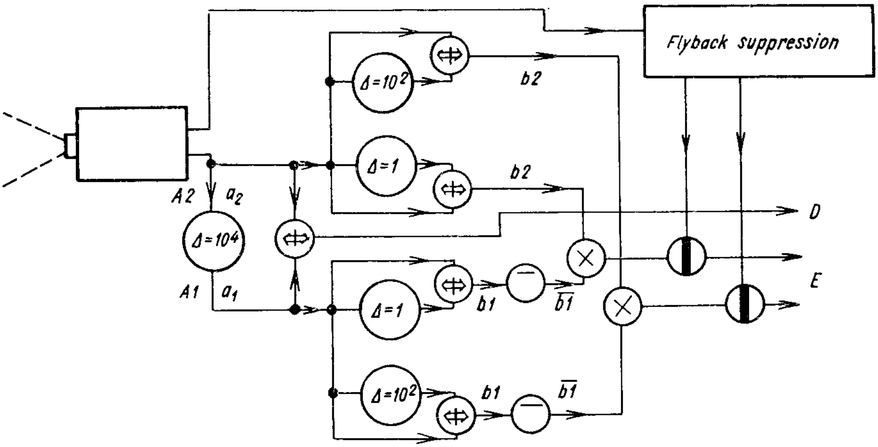


Fig. 16.10. Logic diagram of an analyser serving to derive the sets **D** *and* **E**

on the retina serially, line after line. With this arrangement, the following components are required to obtain set **E**:

a) A delay line for 10^4 bits which – for the given example – may be realized, for instance, by a magnetic tape,

b) Two delay lines for 10^2 bits each, for which further tracks of the same tape might be used,

c) Two delay lines for 1 bit each,

d) Four equivalence elements, two AND elements and two negaters,

e) A circuit for the suppression of signals at the end of the lines and at the end of the columns (flyback suppression), together with two gates.

Considering that the scanning of the dots on the retina can be synchronized with the action of the delay lines by means of clock pulses picked up from the tape, it is clear that the device can be very well re-

alized at the present with the aid of current engineering resources. When we want the set **D** or **E** to be recorded in the memory so that the equi-positioning of the corresponding signals is maintained, it is convenient to use for this purpose the remaining free tracks of the magnetic tape employed.

16.13 An Example of the Operation of an Analyser Realized According to the Block Diagram in Fig. 16.10

Fig. 16.11 illustrates an example of the operation of the analyser shown in Fig. 16.10. The example has been chosen so that it will

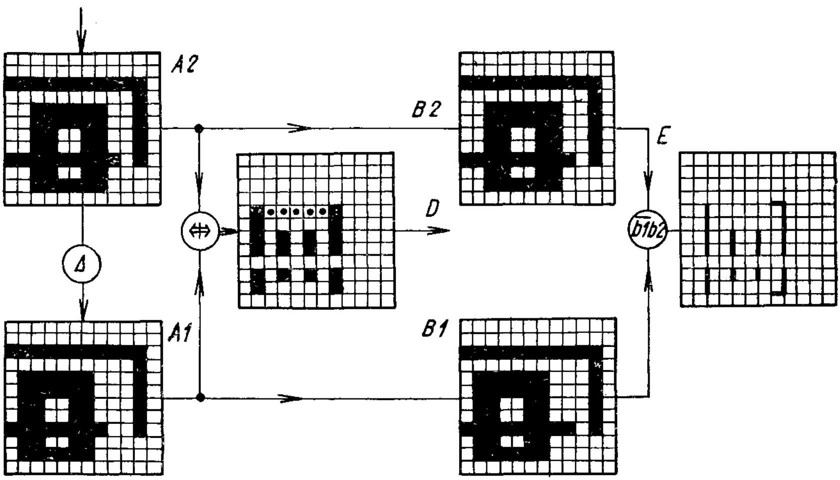


Fig. 16.11. Example of operation of the analyser shown in Fig. 16.10

be possible to apprehend clearly some of the facts which, in the foregoing section, have not been dealt with in detail.

The first image to appear on the retina of the sensor will be $\mathbf{A}_1$. From this image alone it will be impossible to say anything about what belongs to the object and what to the background. The only facts which can be derived for our purposes from a single image are the boundaries which can be ascertained on the image. The same applies to image $\mathbf{A}_2$.

Comparing the two images by means of the non-equivalence according to Eq. (16.1), we obtain the set **D** shown in the centre of Fig. 16.11. Let us note that set **D** no longer contains anything belonging to the background, in other words to the part which has not moved. This statement seems open to the objection that the whole rectangle has moved, a fact which was not registered by set **D**. This objection, however, is not justified. For instance, let us note the equi-positioned picture elements in the images $\mathbf{A}_1$ and $\mathbf{A}_2$, marked by dots in the illustration of set **D**. To be quite accurate, we cannot state that these spots have also shifted. It might happen that in this place the object does not hide the background, but that the background itself is black so that it might seem as though the upper edge of the object were straight. The fact that the marked picture elements do belong to the object which has moved does not follow and cannot follow from a comparison of the two images, but is the result of our own deduction based, for instance, on experience. We therefore consider it to be correct that the visual percept and its possible preliminary treatment should pass only such information to the computer, which unambiguously follows from observation. The completion of the pattern based on this information is then a matter for the program which must determine the method of how to supplement the missing information, for instance by assuming that this or the other picture element belongs to the object, or whether to scan yet another image. Of course, the examples quoted show clearly that the function of the analyser, as described, must be extensively supplemented by the program; they are only used to illustrate this function. On the other hand, we are convinced that even a visual sensor fitted with an analyser capable only of this relatively simple function can be effectively employed in many processes.

The right-hand side of Fig. 16.11 illustrates the outlines of the patterns $\mathbf{A}_1$ and $\mathbf{A}_2$ in the shape of the patterns $\mathbf{B}_1$ and $\mathbf{B}_2$ obtained according to Eq. (16.3), which we called transformation **R**. The pattern **E** then illustrates set **E**, derived according to Eq. (16.5). This shows only those boundaries which have really moved and which appeared in pattern $\mathbf{A}_2$. The completion of the missing boundaries is again, as in the preceding case, a matter for the method which we intend to use for this purpose.

From the viewpoint of their further application, the principal difference between the sets **D** and **E** is that set **D** depends on the magnitude

of the changes associated with the shift of the object, whereas set **E** does not. All the same we are aware of the fact that this definition of the difference between these sets is incomplete. In spite of this limitation, it teaches us to resort to set **D** whenever we want to predict the area in which the object will appear in the next image. Conversely, when concerned with an accurate determination of the shape of an object and its momentary position, we shall prefer using the set **E**.

Another objection which might be raised is that the sets **D** and **E** need not present reliable starting points for the operation of the sensor or of its analyser since, under certain circumstances, they may distort the given situation. This objection is certainly justified. In our opinion, however, it should rather be used to emphasize the necessity of using the sensor correctly or of setting up a program which should control the operation of the sensor so as to prevent it from accepting information when the object moves against a background which is hard to distinguish. For lack of a suitable term, it may be said that it is a question of "stage management" whether the sensor will be able to operate correctly or not. Let us remind the reader of the situation when a television spectator views the picture of a figure clad in a chequered suit against a chequered background. It will be very strenuous and sometimes even impossible to follow the scene, since the resulting percept does not permit the figure to be distinguished from its environment. In this case nobody will blame the spectator for bad eyes or a faulty perception, for having a reduced power of observation, or for using incorrect methods. On the contrary, in such a case we must admit that it is the environment which makes it difficult to follow the object in it.

16.14 Perceptional Algorithms

The fundamental operations described are by themselves insufficient to enable the machine to distinguish an object from its environment. These operations must, of necessity, be included in a process which will utilize them to set up the correct picture of the object. Of course, there are cases when a correct discrimination is impossible. In such a case, the living system supplements the missing information by

its own considerations. Up to the present we have no accurate knowledge of such considerations concerning, for instance, observations carried out by human beings. We only know that not all people observe in the same manner, and we divide them into several groups according to the manner in which they supplement the missing information. We speak of persons having a vivid imagination, at other times of people having good powers of observation, of accurate observation, etc.

We are in a similar situation when using a visual sensor with a machine. It is possible to set up various rules of observation, which we call *perceptional algorithms*. According to the manner of their construction, they will remind us to a lesser or greater degree of the cases where man tries to supplement as much of the missing information as possible and of cases where he limits this supplementation and prefers to wait for further information according to how the situation develops.

Conceived in this manner, the perceptional algorithm has two tasks. The first of these is to ascertain what belongs undoubtedly to the object which moves across the visual field. Its second task is to enable the machine to supplement all that cannot be ascertained with absolute certainty, but of which it is possible to presume with a high degree of probability that it also belongs to the moving object. This second task of the algorithm can be compared, to a certain degree, to the interpolation or extrapolation of a continuous curve represented by concrete values. In connection with the setting-up of perceptional algorithms it will be necessary to deal in the future with theoretical considerations which would exactly define the conditions under which a given algorithm will be applicable. We are not going to treat these problems in greater detail. However, an example will be presented of a perceptional algorithm and of its application to a simple situation.

16.15 Example of a Perceptional Algorithm

The perceptional algorithm presented in this section is intended to find the shape of a black object moving against a static background from two successive pictures, the first of these being used only to determine changes in the pattern.

The following symbols will be used: $\mathbf{A}_1$ – first picture, $\mathbf{A}_2$ – subsequent second picture, $\mathbf{B}_2$ – boundaries found in picture $\mathbf{A}_2$, $\mathbf{E} \equiv \mathbf{C}(\overline{\mathbf{A}}_1 \,.\, \mathbf{A}_2)$. The algorithm consists of the following steps:

1. $\mathbf{E}$ is generated by means of the pictures $\mathbf{A}_1$ and $\mathbf{A}_2$.

2. The black and white side of every boundary is marked in $\mathbf{E}$ according to $\mathbf{A}_2$.

3. In the pattern obtained according to para. 2 we seek out in every line all those pairs of black picture elements, between which there is no boundary on the same line. The picture elements lying inside these pairs are then blackened in all places where equi-positioned black picture elements lie in picture $\mathbf{A}_2$.

4. In the pattern obtained according to para. 2 we seek out in every column all those pairs of black picture elements, between which there is no boundary in the same column. The picture elements lying inside these pairs are then blackened in all places where equi-positioned black elements lie in picture $\mathbf{A}_2$.

5. The patterns obtained according to paras. 3 and 4 are added.

6. In the pattern obtained according to para. 2 we seek out all those picture elements which have not been used in paras. 3 and 4. Picture elements equi-positioned with those having a line boundary are supplemented in the pattern of para. 5 by their neighbour, provided that the equi-positioned element of this neighbour in pattern $\mathbf{A}_2$ is black. If, in $\mathbf{A}_2$, the equi-positioned element of the further neighbour of the newly obtained element is black, then this element must be supplemented by another black neighbour. We proceed in this manner until we come up against a white picture element in $\mathbf{A}_2$, and then stop. This procedure is also interrupted when in the direction, in which new neighbours were created, there is no other column containing in the pattern of para. 2 at least one black picture element, even though the further equi-positioned element in pattern $\mathbf{A}_2$ were black. The procedure described above is repeated in all lines.

7. The procedure performed according to para. 6 upon all lines of the pattern obtained by means of para. 5 is now performed upon all columns in this pattern. As starting points we use all picture elements from the pattern of para. 2 which have not been used in para. 4 and which are

marked by a vertical boundary. All that has been said in para. 6 about lines, applies here to the columns and vice versa.

8. The patterns generated according to paras. 6 and 7 are added into one pattern.

9. The pattern of para. 8 is supplemented with all boundaries.

10. The product is obtained of the boundaries produced according to para. 9 and those of pattern $\mathbf{B}_2$.

11. The boundaries produced according to para. 10 are appropriately marked on their white and black sides in accordance with pattern $\mathbf{A}_2$.

12. The procedures described in paras 3 to 11 are performed once again in succession, omitting para. 10. On completing the procedure of para. 11 we obtain a pattern which represents the final picture of the looked-for object. Its boundaries then represent the final boundaries.

Note: If the picture of the object merges with its background, we cannot decide whether the object moves in front or behind the background. According to this, the common part should belong to whatever is nearer to the sensor. The algorithm described above supplements the object as though it were nearer to the sensor than the background.

16.16 Example of the Behaviour of a Perceptional Algorithm

Figs. 16.12 and 16.13 show examples of a simple object of rectangular outline moving from left to right in the visual field of a visual sensor which observes the object with the aid of the perceptional algorithm described in the foregoing section. Fig. 16.12 illustrates in detail the operation of the algorithm. The pictures $\mathbf{A}_1$ and $\mathbf{A}_2$ scanned successively by the same sensor are presented as the first two patterns in Fig. 16.12. The following patterns are numbered in accordance with the corresponding rules of the algorithm. Each pattern as shown illustrates the situation after the correspondingly numbered rule has been applied. As evidenced by Fig. 16.12, the algorithm operates by first determining the boundaries of both pictures $\mathbf{A}_1$ and $\mathbf{A}_2$. It then establishes the pattern of the boundaries newly created in $\mathbf{A}_2$. It marks the white and black sides of the boundaries thus determined. In accordance with the other rules, from these data it completes the picture, thus obtaining the pre-

sumed shape of the object, and provides the picture with boundaries. The boundaries obtained in this manner represent the presumed outlines of the object. By comparison with $\mathbf{B}_2$ the algorithm ascertains which of these boundaries actually occur on the original picture $\mathbf{A}_2$. The algorithm

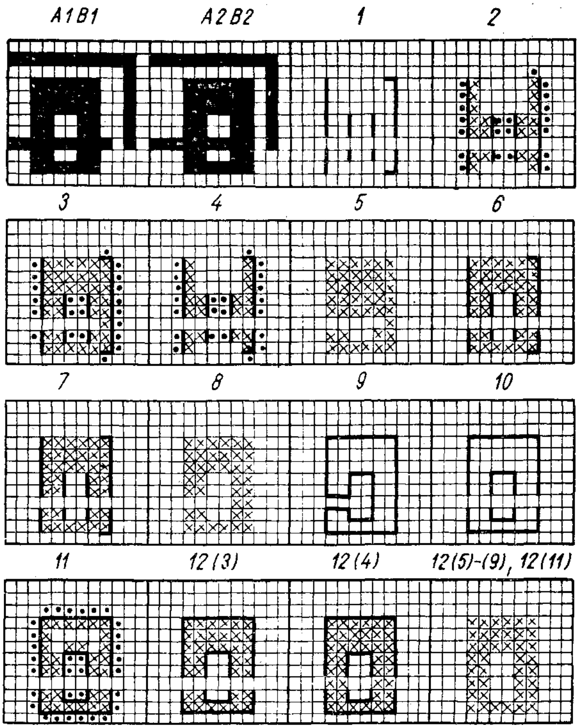
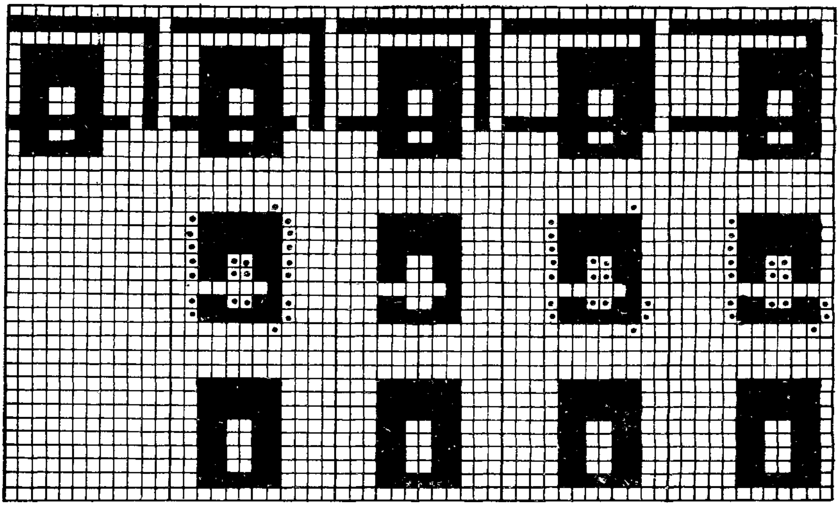


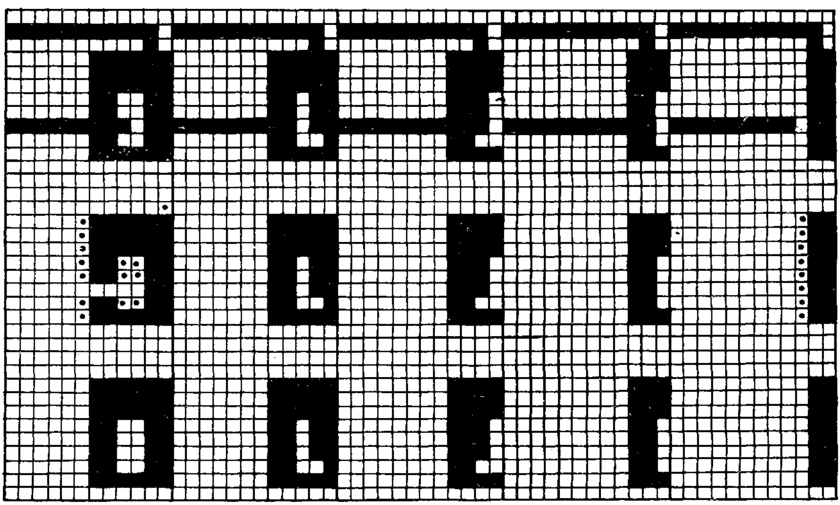
Fig. 16.12. Example illustrating in detail the operation of the perceptional algorithm described in Sec. 16.15. The numbering of the patterns corresponds to that of the rules of the algorithm

thus obtains a new pattern of the boundaries. It then supplements this pattern in the same manner as before to obtain the total appearance of the object, and fills in the boundaries. The algorithm tends to supplement those parts of the object which cannot be ascertained from the two pictures, so as to obtain horizontal and vertical outlines which it places as far



1 2 3 4 5

a



6 7 8 9 10

Fig.16.13. Example of the behaviour of the perceptional algorithm described in Sec. 16.15. The first row (of both top and bottom part) shows a rectangular object moving from left to right. The object moves relative to a static background con-

as possible from the centre of the object, but not further than the furthest actual point of the object. This is why, as our example shows, this algorithm is well suited to the chosen situation, where the object moves in a horizontal direction and has outlines consisting of horizontal and vertical straight lines.

The upper rows of Fig. 16.13 illustrate how the situation develops in the visual field of the visual sensor. The patterns following each other are depicted so as to correspond to the percept of the visual sensor, i.e. in black and white, and so that no boundary can be distinguished in places where the black parts of the background meet the black object. The second row shows beneath each pattern the corresponding appearance of the object as constructed by the algorithm after having applied the first ten rules for the first time. Underneath, in the third row, there appears the final picture of the object obtained after applying rule 12.

When inspecting Fig. 16.13, we must remind ourselves again that the algorithm derives the resulting picture from only two fundamental pictures, one of which appears in the first row directly above the derived picture, the second being to the left of the first one. Thus, when constructing the final picture, the algorithm does not base its operation on a knowledge of previously derived pictures of the object. An interesting situation, which leads to an incorrect interpretation, arises in division 7 of Fig. 16.13, where an entirely new boundary is set up in the pattern in the second column from the right, between the second and third picture element counted from the bottom. Since the boundary here is established as a new one which did not appear in this place on the preceding picture, the algorithm will regard it – in agreement with the rules used – as a moving boundary and will assign it to the object. A similar situation arises in division 8, as far as the vertical boundary inside the object is concerned. These two instances show that, when the shape of the object will have to be ascertained as accurately as possible, it will be necessary

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sisting of a horizontal and an L-shaped bar. The second row illustrates the object as it appears after the application of the first part of the algorithm, the third row shows the object after the full application of the algorithm. In positions 7 and 8 the algorithm cannot ascertain accurately what belongs to the moving object and what does not

to rely not only on a determination of the direction of motion, but also on information derived from pictures obtained formerly. The latter will, in more complicated cases, certainly provide the most important basis for the determination of the correct shape.

16.17 How to Situate the Picture in the Centre of the Visual Field

A facility for situating the object in the centre of the visual field appears to be necessary in all cases when envisaging a controlled rotation or displacement of the visual sensor.

To enable a picture, separated from its environment, to be placed in the centre of the visual field, we must first state when the object will be regarded as being in the centre. There are many ways of defining this convention, and the result depends again on the choice of the programmer. As an example let us present the following method. First let us find the outline of the object (in some cases we content ourselves with the set **E**). We then draw in its vertical axis, its position being determined so that the sum of the distances of all vertical boundaries from the axis is minimal. In a similar way we find the position of the horizontal axis. If the point of intersection of these axes lies in the centre of the retina, the object is said to be in the centre of the visual field.

In this case, the emplacement of the object in the centre of the visual field will be a question of co-operation between the analyser which determines the outline, the computer which ascertains the deviation from the centre, and the motion device which rotates the sensor. If, for this operation, the function of the computer is transferred to the analyser, equipped for this purpose with facilities for ascertaining the deviation, this action of the sensor can be controlled by a single instruction.

The aforesaid method of locating the picture in the centre of the visual field is not the only one possible. The problem of the suitable determination of the centre of the pattern must be studied separately from case to case, in dependence upon the purpose of the relevant sensor, the engineering facilities available, the economy of the device relative to the rest of the computer, and a number of other details.

16.18 How to Track an Object That Alters its Shape

For the sake of simplicity let us assume in this section that we have a single sensor which neither rotates, nor changes its position. Thus, the image of the environment of the object under observation on the retina of the sensor is at rest. In addition, let us suppose that in the visual field of the sensor there appears an object whose outline changes, on the one hand, owing to a rotation of the object relative to the sensor, on the other hand because the object moves away from the sensor or approaches it, so that it alters its apparent size. In some of the initial moments of this action, let the computer transmit to the visual sensor the order to track the object, which is just in its visual field, until the arrival of a different order or until the object disappears from the visual field. Let us further assume that, from time to time, the computer will require the momentary shape of the object under observation to be reported to it for storage in its central memory for its own purposes.

Let us denote the successively scanned patterns as a sequence of sets $\mathbf{A}_1, \mathbf{A}_2, \mathbf{A}_3, \ldots, \mathbf{A}_{(t-1)}, \mathbf{A}_t, \mathbf{A}_{(t+1)}, \ldots$ The sequence of the sets $\mathbf{E}_t$ is determined from two successive patterns $\mathbf{A}_t$, $\mathbf{A}_{(t+1)}$ according to Eq. (16.5), so that we obtain

$$\mathbf{E}_1, \mathbf{E}_2, \mathbf{E}_3, \ldots, \mathbf{E}_{(t-1)}, \mathbf{E}_t, \mathbf{E}_{(t+1)}, \ldots$$

The elements of this sequence are successively stored in the memory of the sensor so that it will always be possible to compare a newly acquired set with the preceding one. As long as the plane patterns of two successive sets $\mathbf{E}$ do not differ too much from each other, the sensor will regard the object in its visual field as the same. The choice of a suitable measure of dissimilarity, which can be defined and ascertained in the most diverse ways, is again a matter for the programmer. If the difference between the new pattern and the preceding one is found to lie inside the chosen measure, the sets $\mathbf{E}$ of the preceding pattern must still be replaced by the new set, so that the subsequent comparison is already performed with respect to the new, altered shape.

As an example of how such a measure is defined, we present a method by which a new set $\mathbf{E}'$ is generated for a given set $\mathbf{E}$ so that to every boundary in set $\mathbf{E}$ we add in all directions one further new boundary

including the diagonals. If now a new set **E** arrives, we construct the intersection of the new set with set **E**′, thus ascertaining whether the new set is fully comprised in set **E**′. If this is so, the new set **E**′ will be declared to differ from the preceding set **E** within admissible limits.

It would certainly be interesting to use, for finding set **E**′, the preceding change in the outline of the object, which would make it possible to track the object in a more flexible manner. Now let us suppose that a new, strange object penetrates the visual field of the sensor while the aforementioned process is going on. Since the new object also moves, its outline will begin to appear as a part of the newly determined set **E**. If the computer would now ask the sensor for the set **E** as representing the momentary outline of the object under observation, together with it there would also appear the outline of the new object. The outline of the strange object must therefore be suppressed.

This can be achieved, for instance, in the following manner. On the basis of the maximum admissible change of set **E** we have, by producing **E**′, simultaneously determined such an environment of **E**, within which its change is still permitted, so that the next set **E** must lie within this environment. (If it does not, we must have committed an error in programming similar to that, when the range of an accumulator is exceeded in an unforeseen manner.) If now, in the newly derived set **E**, an element or a set of elements occurs which lie outside this environment, this strange set must be eliminated from set **E** by a suitable operation. In our case, this operation might be, for instance, the forming of the logical product of **E**′ and the newly derived set **E**. For the modified set **E**, obtained in this manner, a new environment is determined according to the same criterion as for the preceding set. By means of the new environment the outline of the strange object is again eliminated from the next pattern. This method assumes that the object does not deviate from the environment determined for the preceding pattern.

We might ask now what happens when the strange object gets too near to the object under observation. Questions of this kind are closely associated with the problem of the elaboration of suitable methods of observation, a simple example of which is the case described above. It is quite possible that methods will be found enabling the original object to be followed even if the pictures of the original and the strange object

overlap. Of course, cases may occur where a solution will be impossible. Such cases do not substantially differ from situations in which a computer finds itself when some numerator has to be divided by zero. If the computer does not incorporate some blocking device for such contingencies, the situation will be insolvable and it will be a matter for the programmer whether he anticipated this possibility and included the appropriate instructions in the program. Thus, it is not a question of whether the visual sensor by itself or in co-operation with the computer will know how to deal with a given situation, but rather a question of not asking for more than can be achieved with the resources available. Similarly as with other computations, the programmer and the experts concerned with the specific problem to be solved by the visual sensor will have to take great care not to present the computer with an insolvable situation, or to prevent such situations from arising by a suitable disposition of the sensors and by devising suitable programs.

Let us remember that even human beings are sometimes helpless when faced with similar problems of observation. For instance, when observing two men of the same appearance who stop to exchange a few words and then separate, situations may occur such that we will be unable to say after their separation which is which, unless we know in advance some characteristic signs enabling us to distinguish them. It is true that so far there is no experience in the use of visual sensors by machines. On the other hand, we are daily using our own visual percepts to obtain by their aid the information necessary for the solution of the most varied situations. Many a carefully observed situation, however simple, may therefore inspire us to devise a suitable method of how to acquire, by means of visual sensors, the information required by the computer.

16.19 SENSORS AS MEDIATORS BETWEEN THE SYSTEM AND ITS ENVIRONMENT

After having explained the visual sensor as such, it will be useful to turn our attention to the nature of the sensor as an instrument used by the relevant system to communicate with its environment.

Looking about, it seems quite evident to us that there is a house in

front of us because we see it, that we recognize a car approaching because we hear it, etc. Actually, this is by no means as self-evident as we might think. The fact that we see the house in front of us is made possible by a large number of electromagnetic waves of various wavelengths arriving from our surroundings. Let us try to capture this medley of waves as it exists in our environment, but without using a visual sensor. Such an experiment might be performed, for instance, by means of a photographic plate, simply pulled out of its holder for an instant, without using a camera, and then developed. It will be black all over – nothing will appear on it. This is because the incident rays impinged on it quite randomly, without any order, classification or filtering. If we want to obtain a picture on the plate, we must put in front of it an optical system which will arrange the incident waves. Our eye accepts only the wavelengths of so-called visible light. It reacts neither to cosmic and X-rays, nor to radio waves. On the other hand, it distinguishes waves of different lengths in the visible spectrum and thus permits different colours to be perceived. Similarly, the ear does not react to all acoustic waves, but only to a limited range of wavelengths.

However, as far as vision is concerned, it is not only a matter of the discrimination of wavelengths. It is owing to the optical system of the eye that an image is formed on the retina – without the optical system it could not be perceived. The correct formation of the image is a prerequisite of correct vision. The task of the optical system thus consists in arranging the rays arriving in the eye in such a manner that the brain should be correctly informed. This role must also be emphasized to make us realize that we are incapable of receiving information from our environment unless arranged by our sensors, which have a large share in the form in which we accept this information. Let us remind ourselves of the situation when the synchronism of the picture on our television screen is disturbed. At such an instant all the elements of which the picture is composed are still on the screen. In spite of this, the picture is unintelligible. It becomes "readable" again only when synchronism is re-established. This goes to show that it is insufficient to obtain all the elementary information; the decisive thing is at what instant and in which place this information appears in the picture, in other words the code in which we receive the information.

We must also realize that living systems do not accept signals from their sensors passively. Sensations acquired through its sensors are automatically completed by the higher organism to form percepts, i.e. it fills in automatically the gaps of what is frequently intercepted by the sensor in a very imperfect manner. The whole system of perception in the highest organisms is flexible to such a degree that perception adapts itself rapidly to changed conditions owing to systematic (and even subconscious) control. As an example let us quote experiments in which the persons taking the test wore spectacles which turned the image upside down. After a certain period, during which this manner of perception appeared as highly unnatural, the subjects got used to it to such a degree that they no longer noticed perceiving the image in reverse.

Similarly, when a tennis player suddenly starts wearing spectacles, first he will wrongly estimate the distance of the ball, its speed and direction of motion. After a time he will very well adapt himself to the new situation. Therefore, even when speaking of the correct function of the sensor being a condition of correct perception, we do not say thereby what this correct function is. The essential factor seems to be that the sensor should present the facility of correct discrimination, a sufficient amount of elementary sensations and, at a different level, the possibility of distinguishing a sufficient number of various percepts and thus also of various situations. The organism will then find the adequate responses to these sensations, percepts and situations by itself and, if necessary, newly adapt them.

CHAPTER 17

CAN AN INANIMATE SYSTEM LIVE?

In this chapter we want to touch upon some interesting relations between living and inanimate nature. We also want to show that the answer to the paradoxical question put in the chapter heading is far less simple than it might seem at first sight. As we shall see, the difficulty consists chiefly in that, in distinguishing between living and inanimate systems, we base our decision sometimes on the behaviour, at other times on the structure of the pertinent systems. We are going to show that it is just this inconsistency which justifies the paradoxical question quoted.

17.1 THE LIVING AND THE INANIMATE SYSTEM

As soon as we introduce the concept of "*living system*", we divide all systems perforce into two classes. One class comprises *living systems*, the second includes all the remaining systems, i.e. systems which are not alive, that is *inanimate systems*. Let us denote the class of living systems by the symbol **L**, the class of inanimate systems by the symbol **N**. It is clear that it must be possible to fit every system either in the first or in the second class, there being no systems that can be included in both classes simultaneously.

In this context we must realize that a system is included in either class always under certain assumptions. For instance, a virus is included in class **L** only when it is located in a living cell. If it is in some other medium, we include it in class **N**. Having once decided that a system belongs, under specified circumstances, to a certain class, these circumstances must always prevail whenever the system is further investigated.

The concept of "living system" originally arose from the need to distinguish some systems exhibiting peculiar traits in their behaviour

from other systems which do not show these traits. We are here concerned with properties which we have already mentioned in Sec. 9.1. Among these are, for instance, the active exchange of matter and energy between the system and its environment, excitability, reproducibility, etc. From the cybernetic point of view they include the active exchange of information between the system and its environment, which forms the basis for the processes of differentiation, self-organization, etc.

The concept of "living system" thus arose quite naturally on the basis of behaviour. According to the latter we included every system either in class **N** or in class **L**. However, so as to be able to explain secondary manifestations in the behaviour of systems of class **L**, it has proved necessary to study their structure. It appears that all systems of class **L** investigated so far have a highly organized chemical structure – they contain complexes of macromolecular compounds, chiefly proteins and nucleic acids. These compounds have also been found, however, in some systems of class **N**.

On the basis of results obtained in the structural investigation of systems it is possible to enunciate the hypothesis that *macromolecular compounds are a necessary (but by no means sufficient) condition for a system to belong to class* **L**. However, this hypothesis implies the assumption that *every system that does not contain any macromolecular compound necessarily belongs to class* **N**.

Now let us assume that the aforesaid structural investigations of systems have not been concluded yet (an assumption that must always be admitted), or that we are not satisfied with their conclusions. We therefore select some further systems (not investigated so far) of class **L** and submit their structure to a thorough investigation. Let us further assume that we encounter a system (again chosen from class **L**) in which we do not discover any macromolecular compounds but which consist, for example, of inorganic compounds only. Are we entitled to transfer, based on this discovery and with regard to the hypothesis pronounced earlier, the system under investigation from class **L** to class **N**? Certainly not, since the system under consideration properly belongs – according to its behaviour – to class **L**. What can we do to avoid this dilemma? There seem to be only two possibilities:

1. To narrow down class **L** by defining it not only from the standpoint

of behaviour, but also from that of structure, i.e. by using the hypothesis quoted above for a new definition of the class of living systems. Let us denote the newly defined classes of systems by the symbols $\mathbf{L}'$ and $\mathbf{N}'$ respectively. It is clear that $\mathbf{L}' < \mathbf{L}$, whereas $\mathbf{N}' > \mathbf{N}$.

2. To revise our hypothesis which says that macromolecular compounds are a necessary condition for the existence of systems of class $\mathbf{L}$. Otherwise the answer to our fundamental question might be really paradoxical: "Yes, an inanimate system (regarded from the standpoint of structure) can live (regarded from the standpoint of behaviour)".

If we adopt the first solution, we must admit that systems of class $\mathbf{N}'$ may have the same behaviour as systems of class $\mathbf{L}'$. That this is possible is exemplified by the present state of the art of automatic data processing. We know now that an active exchange of matter and energy is possible between machines and their environment, even though it is based on other than biochemical principles. We also know that, in principle, machines are capable of an active exchange of information with their environment; on this basis differentiation, self-organization and even reproduction can occur in machines. Finally, we know that machines are capable of higher psychological manifestations. Thus it is only structure which determines the difference between class $\mathbf{N}'$ and $\mathbf{L}'$.

If we adopt the second solution, the original division of systems into the classes $\mathbf{N}$ and $\mathbf{L}$ remains in force, i.e. we define these classes consequently from the standpoint of behaviour. In that case, of course, we must seek a new structural explanation for the behaviour of systems of class $\mathbf{L}$. We think that investigations in this direction are one of the fundamental tasks facing cybernetics.

There already appears a way out of the difficulties mentioned: The basis of our confusion consists in that the division of systems into living and inanimate ones is too coarse. We must progressively stop dividing systems into living and inanimate ones, and introduce a far more detailed classification according to the degree of organization in systems. Some authors even express the view that the degree of the amount of organization is essentially a measure of the degree to which the pertinent system can be said to live.

Objections may be raised against such an attitude in connection with the fact that living systems always have their predecessors in living sys-

tems again. According to this criterion it would thus be always possible to ascertain whether we are concerned with living or inanimate systems. However, the objection mentioned above is justified to a certain degree only, since:

a) in principle, self-reproduction is possible in inanimate systems, so that we may envisage whole generations of highly organized inanimate systems to emerge in the future,

b) the criterion mentioned above can be applied only to systems originating on our planet; it cannot be used to decide on systems on other planets.

17.2 A Comparison of the Principles of Operation

In the preceding section we pointed out the fact that, from the viewpoint of behaviour, there are no essential differences between living and inanimate systems. The fundamental differencies between the two types of system are thus of a structural nature, and that only at a sufficiently high resolution level. Let us now carry out a rough comparison from this point of view.

The structure of living systems is based predominantly on chemical principles. When information is processed in these systems, this is mostly done with the aid of chemical processes. In inanimate systems, on the other hand, the structure manifests itself in the form of electrical circuits and information is processed by means of electric signals. Does either of the two principles mentioned have any evident advantages from the viewpoint of information processing?

Chemical principles have one indisputable advantage. The basic building stones involved are molecules, so that informational processes proceed at molecular or even atomic level. Living cells are already very complicated systems, which under certain circumstances are capable of independent existence conditional on complicated behaviour. The mechanisms which mediate this behaviour are, of course, also operating at molecular or atomic level. We are thus always concerned with processes which, regarded from the viewpoint of man, proceed in the submicro-

scopic world. This applies not only to the dimensions, but also to the required energy. Owing to the small dimensions and low energies involved, the performance of biological systems as regards information processing and transfer is immense. The situation is similar as far as information storage capacity is concerned. For instance, a simple cell which gives rise to a new individual contains the entire program of its future construction. It is well known that one-egg twins resemble each other so as to be practically undistinguishable until many years after birth. And yet, they grew up independently from the very beginning, i.e. from the germ cell.

How much identical information had to be stored in the first cells of each of them, so that nothing could disturb their mutual resemblance during the complicated process of growth, first in the womb, then in the course of their independent life after birth! Thus, the principal advantage of living systems is their immensely economical utilization of matter and energy. To illustrate this statement, let us quote some well-known facts: The human brain, which produces the most complicated behaviour as yet known, occupies a volume of only 1 dm^3, contains about 10^{10} elements (neurons) and requires only about 10 W of energy for its operation.

As far as economy in the use of matter and energy is concerned, inanimate systems are not nearly as efficient. On the other hand, inanimate systems which employ electrical principles are capable of processing information at a speed many times exceeding that of living systems whose operation is based on chemical principles. In addition, they are capable of transmitting information very rapidly and easily even over large distances.

The main advantage of inanimate systems thus consists in the high speed at which they process and transmit information. Such a speed is inaccessible to living systems. After the first outstanding successes achieved in the design of fast engineering systems for information processing, the main effort of the technologists is now directed towards a reduction in the size of these systems (miniaturization of components) and in the energy required. The aim is to retain the advantages of fast operation while also achieving the advantages of small dimensions and low energy consumption.

Attempts are already being made to utilize chemical principles also in inanimate engineering systems for information processing, for instance in the construction of memories of very large capacity, etc. If these attempts prove successful, we may expect inanimate systems to become more advantageous than living systems from the viewpoint of information processing.

17.3 New Principles of Life

If we contemplate the diversity of living nature, we encounter many interesting and, as yet, unique principles. For instance, the bat finds its bearings in the dark with the aid of miniature ultrasonic locators, by means of which it can determine the distance and shape of objects in its path; the females of some species of insects transmit information about themselves either by emitting smells or infrared radiation which can be picked up by the males at distances of many miles. When sitting on some plant, the grasshopper is capable of perceiving its vibrations even if their amplitude is as small as half the diameter of the hydrogen atom. We could quote a great number of similar remarkable instances occurring in living nature.

In living nature we thus encounter the most diverse, highly developed principles of the communication and processing of information. Some of these principles have already been successfully employed in engineering systems. Many other principles, however, either have not yet been satisfactorily explained, or no suitable technical means have been discovered so far, capable of modelling these principles. The outstanding problem of modelling biological resources of the type mentioned has recently come under very intense investigation in the sphere of bionics.

Considering living systems from the viewpoint of the purpose served by the processing of information, we find this purpose to be the facility of anticipating the future. The living system utilizes this facility to gain enough time for preparing against expected changes in its environment.

Some inanimate systems may also possess the capacity of anticipation; however, this capacity does not reveal itself until the inanimate system begins to rely on an independent attitude towards its environment.

Here we are suddenly faced with a highly delicate and, moreover, extraordinarily important question. Is the facility of anticipating the future the only distinguishing property of highly organized systems? And let us modify this question to make it sound still more urgent: Is the facility of anticipating the future a necessary property of highly organized living systems? A further question crops up in this connection: What other important properties – in addition to the facility of anticipation – may appear in highly organized systems which are as yet unknown to us, and of which we would have to admit that their organization is higher than ours?

So far, our phantasy does not permit us to imagine such systems. This fact seems to be affected to a considerable degree by the viewpoints which we apply to such systems. To illustrate, for instance, how the viewpoint of utility affects our considerations, let us imagine ourselves to be beings who neither know nor need any plants. Let us further imagine that somebody performs a theoretical investigation into the possibilities of chemical reactions and invents plants which, however, he has not yet realized. And now let us meet to discuss this discovery. Our first questions will be as follows: What is the sense of creating plants, what will they do? And if somebody tells us that they will simply form part of living nature, that they will reproduce, serve as food, embellish the environment of man, etc., such reasons will possibly appear to us so paltry, insufficient and futile, that we shall declare this discovery to be of little interest.

In actual nature, things present themselves quite differently. There are plants, there are also animal organisms, and their co-ordination is such that the existence of higher organisms (animals) depends on that of lower organisms (plants). Hence our next question: If there exist, or can exist, highly organized systems, organized higher than we are or organized in a different manner, under what conditions can they exist and what lower systems are necessary for their existence?

We can quite well imagine that in the distant future a special class of machines (inanimate automata) will be created as a social product, which will be higher organisms than individual human beings, for instance in the sense that their behaviour will be more complicated and their capability of survival will be higher. All the same, the long-term existence

of these machines may depend on the existence of man, just as the existence of animals depends on that of plants.

Evolution on our planet is characterized by the fact that the original simple chemical processes have led to more complicated biochemical, biological and, finally, social processes. In this sense, the present is characterized chiefly by the emergence of highly organized systems, which do not genetically follow upon living systems. Nevertheless, they are beginning to acquire capacities for self-organization, reproduction, survival with respect to their environment, etc. How far and in which form have such processes gone on elsewhere, at some other place of our universe? It seems quite likely that a book describing conditions in some other part of the universe would be simply unintelligible, since it would be quite unacceptable to our opinions, criteria and points of view. A serious study of the problems concerned with new principles of life may be of great importance in the future, if we want to understand many of the peculiarities of our universe.

Questions concerning the investigation into new principles of life constitute one of the most complicated problems. In this context it is not sufficient to derive new conclusions from known facts; new points of view, new approaches and new criteria must be established even though they may appear quite unusual to us. However, direct scientific investigation into these problems to this extent has not yet even begun.

17.4 SELF-ORGANIZATION

Organisms possess the peculiar capacity of adapting themselves to their environment. However, they can go farther than that. They are capable od successive improvement by means of stimuli received from their environment. We have seen that not only living, but also inanimate systems can be equipped with such properties, that their behaviour in a given medium or under certain circumstances will, after some time, become better than before. The process which takes place in the system in the course of its improvement is called *self-organization.*

In connection with the self-organization of systems we are concerned with several problems. So as to be able to speak of self-organization, the

system in which self-organization takes place must already have arrived at some higher degree of organization. The question as to what a system must be like to be capable of self-organization is one of those which is being intensely studied at the present. Another question is, under what external conditions self-organization can arise in systems. These problems must also be thoroughly investigated, along with those listed above [A27, A28, A30, C24, C43].

What is the significance of self-organization in inanimate systems? The question of self-organization is associated with the improvement of the system after its creation, i.e. at a time when its creator can no longer influence it. It is certainly of extraordinary interest to work one's way through to an answer to the question, to what degree an inanimate system – created, for instance, by man – can later improve itself, and in what way it can acquire properties which were not even thought of when it was created. Similarly it would be interesting to know the boundaries of the growth of a system from the viewpoint of its organization. How are such processes going to be governed? How will they develop? When will this evolution be beneficial, and under what conditions could it become detrimental? We have seen that inanimate systems, past and present – let us mention only rockets – can serve mankind, but can also endanger it. How about systems which will, moreover, be able to improve upon themselves? And, in particular, in what way will it be possible to use them for the general benefit of humanity?

Not only answers to such questions, but also to questions of the generation of self-organizing processes and their control, i.e. the discovery and determination of possibilities concerning their adjustment, regulation and supervision, will in the future lead to progress in a direction where we may encounter many a surprise.

17.5 SELF-REPRODUCTION

In the literature we find many studies dealing with the question of whether and under what conditions inanimate systems are capable of producing further inanimate systems possessing properties similar to those of their inanimate progenitors. Such a process, which is analogous

to the process of reproduction in living systems, is called *self-reproduction*. According to our present state of knowledge there are no obstacles to the possibility of such a process of self-reproduction. We may very well admit that production in a factory can be controlled quite automatically by a digital computer. We may just as well envisage the program of such a computer to be set up so that the factory will produce digital computers into which, on their completion, the entire program of the original computer will be inserted. The digital computer thus produces a system identical with itself.

This idea may be expanded by imagining that the program of the computer contains not only instructions to reproduce itself, but also to reproduce the whole factory in which it was made. The computer will then, for instance, remotely control the erection of the new factory, produce the necessary tools and assemble them at a distance. At the same time it will reproduce itself and, when ready, insert the new computer into the newly erected factory together with a program copied from its own program. Thus, there will be two factories, each of which will be capable of producing another identical factory.

A still more interesting case is represented by the possibility against which no objections can be raised on theoretical grounds, either – consisting in that the digital computer, which produces a further computer, operates on the basis of experiential and similar higher methods (see Chapter 12). After producing the new computer, the first computer will pass to it not only its original program, but also the contents of its experiences, on which the new computer can base its operation. The sequence of computers produced in this manner will then have the property that successive computers will be better and better in the sense that they will operate on the basis of the experience of all their predecessors, which they will supplement by their own experience.

Such a process has not yet been realized in practice, first of all because of the high cost involved, secondly because the very elaboration of a detailed project of this kind would be far too exacting. On the other hand, the evolution of technology clearly indicates that in future it will be possible to construct systems the behaviour of which will, no doubt, be increasingly complex, while the technical demands made on their construction will become increasingly simpler.

It seems therefore that the time is not far off when the first processes of this kind will be realized. At the present, the investigation of such processes is confined to theoretical studies, verified by simplified processes on digital computers.

17.6 WHAT DOES THE SIMPLICITY AND COMPLEXITY OF HIGHLY ORGANIZED SYSTEMS CONSIST OF?

At the end of the preceding section we mentioned that the technical demands on the construction of a system are reduced if the elements, of which the system consists, are improved. From this viewpoint it is important to realize that an interesting development is taking place in the construction of digital computers. Modern digital computers are no longer built of electronic valves, semiconductors, resistors and similar components. The construction and activation of modern computers requires that these basic components be first grouped together in self-contained units, so-called modules. These modules, of which there are only a few different kinds in the computer, are produced in large numbers and form the basic element of the computer. Before being installed in the computer, every one of these modules it first independently tested and either accepted or rejected. The elements thus obtained form elementary organized systems used for the assembly of higher elements – the units of the computer. If we then consider, for instance, a medium-sized digital computer fitted with scores of peripheral devices, scores of memories of several types, etc., we see that technology actually copies – in a certain sense – what nature has been doing to a far greater measure for ages in its workshop, in which it creates living systems, beginning from the lowest and ending at the highest ones.

Let us here remind the reader of metabolism, which proceeds so that higher animals use as food, in addition to inorganic substances, also lower animals and their products, together with plants. Through the food thus absorbed they also receive substances which serve not only for the regeneration, but also for the construction of their own organism – substances which the organism itself is incapable of producing in any other manner. They thus permanently receive "elements" which, as such, are

already highly organized systems, for instance high-molecular compounds of the most diverse kind, etc.

If we consider this situation from the viewpoint of the evolution of highly organized systems, we see that their development and existence depend on the existence of lower organisms. When we expand this consideration, a question arises which cybernetics is at least attempting to answer: what will systems be like, which are not yet known and whose emergence will depend on the existence of man?

At the same time we must realize that at the present we already know systems which are relatively highly organized and whose existence actually depends on man. These are all the systems produced by human beings. But even the highest of them, the digital computer, is at a very low level from the viewpoint of its organization when compared with man.

One thing, however, clearly emerges from these considerations: Man, in his endeavour to create systems of ever-increasing complexity and perfection, with higher and higher behaviour and organization, only follows the evolutionary path outlined by nature long before it created man. Therefore, even if the efforts of man would lead to the generation of a system which would be far more perfect in its properties than man himself, he neither can nor does act contrary either to nature and its laws, or to the line of evolution, in which he participates by this effort.

And finally, regarding this matter without bias, we cannot but admit that nature, in the same manner as it feeds and builds higher systems with the aid of lower systems, utilizes our own endeavour to pursue its course, begun long ago and without our aid.

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